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HIGH-TEMPERATURE MINERAL ASSOCIATIONS AT SHALLOW TO MODERATE DEPTHS.

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IN a discussion of the principles of genetic classification of mineral deposits, Lindgren [1] wrote: "The genetic classification should ultimately determine the limits of ore deposition in each class by temperature and pressure." In practice, depth and temperature were used by him, and three major groups defined for "mineral deposits dependent upon the eruption of igneous rocks and formed by hot ascending waters of uncertain origin but charged with igneous emanations."

There are nine possible combinations of temperature and depth (or pressure) if high, intermediate, and low ranges for each are considered. Of these only three appear directly in Lindgren's classification. It is probable that natural conditions are such that one of the possible combinations does not often, if ever, occur, such as, for example, great depth—low temperature. In other cases the products formed under two different combinations of temperature and depth may be so similar that for the present it is impractical, or not sufficiently worthwhile, to use them in classifying mineral associations; as, for example, intermediate depth—high temperature, which are so similar to great depth—high temperature, both being classified by Lindgren as hypothermal. Deposits formed at great depth and intermediate temperature are grouped with those formed at intermediate depth and intermediate temperature. Deposits formed at shallow depths and intermediate temperature are probably common but difficult in many cases to distinguish from shallow depth and low temperature. The

[1] Lindgren, Waldemar: Mineral Deposits, pp. 178–188. McGraw-Hill, 1913.

gold-wolframite deposits of the northern Black Hills [2] (depth of formation 3000–3500 feet) may represent an example; the quartz veins of the Bonanza district, Colorado, described by Burbank [3] as of moderate sulphide content and containing barite, pyrite, sphalerite, galena, chalcopyrite, bornite, tennantite, and stromeyerite, are so classified by him; and the ferberite [4] deposits of Boulder County, Colorado, may belong to this class. Deposits of dolomitic zinc-lead type in the Weston Pass district, Colorado, interpreted as formed at low temperatures but at a depth of perhaps as much as 10,000 feet, are described by Loughlin and Behre.[5]

Graton [6] has proposed the term "leptothermal" for deposits comprising the top of Lindgren's mesothermal and the bottom of his epithermal group, and thus standing between the two.

Spurr [7] in particular has emphasized the possibility of high temperature deposits at shallow depths, and writes:—"That shallow depth has meant low temperature, during periods of ore deposition, is as fundamental an error as has been made in our recent literature of ore deposition." Niggli [8] writes:—"The question, however, arises whether all the deposits included under 'epithermal' were actually formed at lower temperatures than those of the mesothermal group."

A search of the literature and a grouping of mineral associations probably formed at high temperature and shallow to moderate depths shows such a number, diversity, and particularly such marked peculiarities as to definitely warrant the establish-

[2] Connolly, J. P.: The Tertiary Mineralization of the Northern Black Hills. S. Dak. School of Mines, Bull. 15, pp. 95–98, 1927.

[3] Burbank, W. S.: Geology and Ore Deposits of the Bonanza Mining District, Colorado. U. S. Geol. Survey, Prof. Paper 169, p. 86, 1932.

[4] Lovering, T. S.: Ore Deposits of Nederland, Central City, and Idaho Springs. Guidebook 19, XVIth Int. Geol. Cong., pp. 140–143, 1933.

[5] Loughlin, G. F., and Behre, C. H. Jr.: Zoning of Ore Deposits, Leadville District, Colorado. ECON. GEOL., vol. 29, pp. 239–240, 1934.

[6] Graton, L. C.: The Depth Zones in Ore Deposition. ECON. GEOL., vol. 28, pp. 536–540, 1933.

[7] Spurr, J. E.: Review of "Geology and Ore Deposits of the Randsburg Quadrangle, Cal," by C. D. Hulin. Eng. & Min. Jour., p. 463, 1926.

[8] Niggli, Paul: Ore Deposits of Magmatic Origin, p. 33. Murby & Co., 1929.

ment of a separate pigeonhole for these deposits, although only a few of them are the basis of great mines.

In general, the mineral associations cited in this paper as of high temperature and shallow to moderate depth are thought to have been formed at or below a depth of 2000–3000 feet from the original surface at time of deposition. It is impossible to give a figure for the lower limit, but certainly it would be at least as much as several thousand feet deeper. This range would appear to correspond very closely to that given by Graton for the proposed group of "leptothermal deposits."

Two quotations will serve to introduce the general principles involved in high temperature—shallow depth mineralization. Spurr [9] writes:

> This chapter deals with those ore deposits formed within a few thousand or even a few hundred feet of the surface, mainly in Tertiary surface volcanics. These sometimes represent all the metals of all the plutonic ore-sequence zones; I infer that they have been formed at the same critical temperatures as the latter, but that the fall in temperature has been so rapid that the superposition of one upon another has resulted in "telescoping" so that the whole vertical range is sometimes compressed within a single shallow-formed set of veins.

Graton [10] writes:

> Telescoping probably represents merely hurried and promiscuous precipitation caused by rapid loss of heat and pressure as the ascending solutions are dissipated into the highly fractured and colder rocks nearer the surface. It . . . is especially likely to occur where the geothermal gradient is abnormally steep because of the near-surface cooling of hot effusive rocks. . . . In such instances the solutions would have moved upward for indefinite distances along pre-heated channelways. . . . In so far, therefore, as rate of heat-loss affects mineral precipitation, solutions under these circumstances would cause deposits characteristic of the deeper zones to be extended, or "stretched" as one might say, to abnormally shallow levels. . . . Indeed, . . . telescoping may be so extreme as to bring minerals characteristic of great depth up to those shallow levels where normally epithermal ores would naturally be expected.

The rocks in which the mineralization is effected are often somewhat porous, crackled, or fissured. This fact viewed in the

[9] Spurr, Josiah E.: The Ore Magmas, p. 292, 1923.

[10] Graton, L. C.: *Op. cit.*, pp. 544–545.

light of the high temperature of the solution, and the shallow to moderate depth and consequent low pressure, suggests that the mineralization must have been in part formed by pneumatolysis and in part deposited from the liquid solution as a result of distillation as well as by relatively rapid cooling. The precipitation under conditions of pneumatolysis, distillation, and rapid cooling, results in the peculiar mineral associations and peculiar characters which are found.

The deposits are characteristically of the cryptobatholithic type (near hidden batholiths which have not yet been exhumed by erosion) as defined by Emmons.

Such minerals as magnetite, specularite, apatite, tourmaline, topaz, orthoclase, augite, diopside, and phlogopite are, with certain qualifications, commonly considered to be diagnostic of high-temperature origin for the mineral associations of which they form one member, and are so used in this paper. The formation of these minerals at a high temperature in the deposits here considered is suggested by the fact that they may be followed successively by typical intermediate and low-temperature mineral associations in the same vein. In the deep high-temperature deposits all these minerals are usually well crystallized, and in aggregates are medium to coarse-grained; in the high-temperature deposits of shallow to moderate depths, the tourmaline and topaz are commonly fine-grained; the tourmaline, pyroxene and apatite generally have a fine radiate prismatic or needle-like habit; the cassiterite (in part intergrown with specularite) usually has a colloform structure with radiating fibers; platinum appears with colloform structure in the Waterberg deposits, and the quartz that is associated with the deposits is commonly fine-grained, uneven in grain, of cherty or porcelain-like character, or may even be chalcedonic. Apatite is a common accessory gangue mineral. The occurrence of high-temperature minerals with dense fine-grained or chalcedonic quartz is characteristic of many of these deposits. Pyrrhotite is rarely present, presumably because of the low pressure and high temperatures obtaining. It is also noteworthy that adularia is but rarely present.

The common occurrence of a different mode of crystallization in lavas as distinguished from plutonics may also be noted here, such as a single feldspar (sanidine) in place of orthoclase *and* albite, or a single pyroxene (pigeonite) in place of a diopsidic *and* hypersthenic pyroxene.

A mineral association of high temperature—moderate to great depth, which has not been found at shallow depths, is that characteristic of complex pegmatites comprising such minerals as the alkali tourmalines, beryl, lepidolite, spodumene, or albite. This point has been strongly emphasized by Niggli.[11]

Data on wall-rock alterations and replacements are inadequate for a proper discussion. Three types may certainly be distinguished. Magnetite (martite) deposits may be accompanied by the replacement of the wall rock by such minerals as diopside, augite, actinolite, biotite, phlogopite, apatite, tourmaline, and calcite. A common development which may occur with all types is a fine-grained to porcelain-like siliceous replacement of the country rock. A third common type of alteration consists of sericitization and tourmalinization of the country rock.

Kaolinitization, alunitization, and the formation of sepiolite are also reported in association with these deposits, but probably belong to the late-stage lower-temperature ranges of formation.

Some may question as to whether the deposits here discussed were really formed at high temperatures, and it must be admitted that the evidence available is not conclusive. But whatever one's opinion as to the temperature of origin of such deposits, the writer believes that the conclusion of McLaughlin,[12] after describing several deposits carrying tourmaline but formed at shallow depths, that " the hypothermal group would be a more consistent and compact unit if such deposits were not included " will still be true.

The writer therefore proposes the term *xenothermal* for these deposits, from the Greek *xeno* meaning strange, different, foreign, and hence suggestive of the peculiar textures for the normal high-temperature mineral assemblages involved, of the abnormal

[11] Niggli, P.: *Op. cit.*

[12] McLaughlin, D. H.: Hypothermal Deposits. Ore Deposits of the Western States (Lindgren Volume), Ch. XI, Pt. IV, p. 569.

association of high temperature with shallow depth, and of the "telescoped" character of many of the deposits.

Deposits formed primarily as the result of distillation or boiling of high-temperature solutions at shallow depths might aptly be termed zeothermal [12a] deposits from the Greek zeo (to boil), but the writer is not certain how far this mode of origin applies to the deposits here included under the term xenothermal.

TABLE I.

Temperature	Depth	Deposits
50°–200° C. ±	Shallow	EPITHERMAL
	Moderate	Dolomitic zinc-lead deposits, Weston Pass Dist., Col.
	Great	Not to be expected
Upper part of 50°–200° C. temperature range and lower part of 200°–300° C. temperature range.	Lower part of shallow and upper part of moderate as used by Lindgren.	LEPTOTHERMAL
200°–300° C. ±	Shallow	Difficult to distinguish. Gold-wolframite deposits, northern Black Hills, S. D. Complex sulphide-quartz veins, Bonanza District, Colorado.
	Moderate	MESOTHERMAL
	Great	Probably not common, and characters would not differ greatly from mesothermal deposits.
300°–500° C. ±	Shallow	XENOTHERMAL
	Moderate	HYPOTHERMAL
	Great	

In Table I, the relationship of the xenothermal deposits to the others is shown in summary form.

Table II lists the major types of mineral associations dependent upon the eruption of igneous rocks, and formed by solutions at

[12a] Suggested to the writer by Fred Jolliffe.

TABLE II.

MINERAL ASSOCIATIONS INTERPRETED AS FORMED AT HIGH TEMPERATURE—SHALLOW TO MODERATE DEPTHS.

A. Genetically connected with intrusive igneous rocks:

(1) Pyrometasomatic mineral associations:

Tintic, Utah;[13] Enstatite, spinel, garnet (andradite), magnetite, diopside, tridymite. Depth about 3000 feet.

Marysville, Mont.; [14] Feldspars, mica, hornblende, tremolite, diopside, epidote, garnet, pyrite, magnetite, tourmaline, apatite. Shallow depth.

Snoqualmie, Wash.; [15] Magnetite, garnet, hornblende, quartz, calcite, pyrite. Depth about one mile.

(2) Fissure fillings and (or) replacements: (Xenothermal Deposits).

Platinum: Waterberg, Transvaal, S. Africa.

Magnetite (martite)—apatite-pyroxene: Cerro Mercado, Mexico; Algarrobo, Chile; etc.

Cassiterite and cassiterite-wolframite: Ikuno-Akenobe District, Japan; Lallagua, Bolivia.

Molybdenite-orthoclase-quartz: Climax, Colorado.

Scheelite: Atolia District, California.

Tourmaline-cherty quartz or jasperoid: Southern Oquirrh Mts., Utah; Oregon Cascades.

Tourmaline-chalcopyrite: Braden, Chile; Cactus Mine, Utah.

Miscellaneous.

(3) Druse fillings in hypabyssal intrusives:

Microperthite, orthoclase, albite, quartz, biotite, riebeckite, ilmenite, specularite, etc.

(4) Aplite dikes and related replacements (often epidote) in hypabyssal intrusives.

B. Genetically related to lava flows:

(1) Druse and cavity fillings, veinlets, lithophysae, etc.:

Topaz-beryl-spessartite-bixbyite-specularite-pseudobrookite-quartz: [16] Thomas Range, Utah.

Tridymite-sanidine-cristobalite-fayalite-quartz: [17] Obsidian Cliff, Yellowstone National Park.

Sanidine-plagioclase-sodalite-biotite-augite-fayalite-fluorite-breislakite (fibrous ilvaite)-cuprite-apatite: [18] Vesuvius.

(2) Pegmatitoides: [19]

Nepheline, analcite, feldspars, magnetite, ilmenite, pyroxenes, and amphiboles.

(3) Sublimates and pneumatolytic alterations:

Magnetite and specularite [20]—Katmai * (250°–650° C.).

Banded opal (about 350° C.)—Katmai * (pages 27 and 28).

* Fenner suggests derivation from sub-surface intrusive sheet.

[13] Lindgren, W., and Loughlin, G. F.: Geology and Ore Deposits of the Tintic Mining District, Utah. U. S. Geol. Surv., Prof. Paper No. 107, pp. 94–97, 1919.

(*Footnotes continued on next page.*)

shallow to moderate depth and high temperature, together with specific examples. The mineral associations in the groups other than "Fissure Filling and (or) Replacements" are included primarily as supporting evidence to emphasize the concept that high-temperature minerals may form at shallow depth under a variety of conditions; they will not be discussed further.

XENOTHERMAL DEPOSITS.

Platinum.—The platinum deposits of the Waterberg district in the Transvaal, Africa, afford a most unusual type of deposit for this metal, and one which is ascribed by Wagner [21] to an origin under conditions of high temperature near the surface. According to Wagner, the mineral deposits take the form of brecciated quartz lodes occupying faults of post-Karroo age in felsite and felsite-tuff belonging to the Bushveld Igneous Complex. The filling consists of quartz stringers exhibiting comb-structure, banding, and crustification, with development locally of cockade structure; the minerals comprise specularite, sericite, chromiferous chlorite, and platinum; the early platinum is as a rule intimately intergrown with specularite and is in part in colloform, globular, and reniform grains; a later-stage platinum forms minute microscopic grains imbedded in secondary iron oxide evidently derived

[14] Barrell, J.: Geology of the Marysville Mining District, Montana. U. S. Geol. Survey, Prof. Paper 57, pp. 121–150, 1907.

[15] Smith, G. O., and Calkins, F. C.: Snoqualmie Folio. U. S. Geol. Survey, Folio 139, 1906.

[16] Palache, Charles: Minerals from Topaz Mt., Utah. Amer. Miner., vol. 19, pp. 14–16, 1934; Patton, H. B.: Topaz-bearing Rhyolite of the Thomas Range, Utah. Bull. Geol. Soc. Amer., vol. 19, pp. 177–192, 1908.

[17] Foshag, W. F.: The Minerals of Obsidian Cliff, Yellowstone National Park, and their Origins. U. S. Nat. Mus. Proc., vol. 68, art. 17 (18 pp.), 1926.

[18] Lacroix, A.: Produits silicates de l'eruption du Vesuve, 1907. Quoted by Fenner in Ore Deposits of the Western States (Lindgren Volume), p. 99, 1933.

[19] Kennedy, W. Q.: Amer. Jour. Sci., vol. 25, pp. 242–247, 1933.

[20] Zies, E. G.: The Valley of Ten Thousand Smokes—(1) The Fumarolic Incrustations and Their Bearing on Ore Deposition. Natl. Geog. Soc. Tech. Papers, vol. 1, no. 4, 1929.

[21] Wagner, P. A.: Platinum Deposits and Mines of South Africa, pp. 257–263, 1929.

from oxidation of pyrite; the platinum is alloyed with more or less palladium and a bit of gold.

Attention may also be called to the Boss mine in the Yellow Pine Mining District, Nevada, where, as described by Knopf,[22] an auriferous platinum-palladium deposit represents in the main an oxidized fine-grained siliceous replacement of dolomite along vertical fractures, the ore minerals comprising extremely fine platinoids with very fine spongy gold and a little associated rutile and octahedrite.

Magnetite (martite)-Apatite-Pyroxene.—Geijer [23] has described as the " Kiiruna Type "

> ores of magnetite (or rarely hematite), with a moderate to low amount of gangue minerals; fluorite apatite is generally conspicuous, and amphibole or pyroxene often appear, but other minerals are, on the whole, to be regarded as occasional accessories; the titanium content is low, TiO_2 rarely surpassing 1 per cent.; sulphur is generally low. The deposits are closely connected with igneous rocks that are mostly of an intermediate or moderately siliceous character and that have, with few exceptions, solidified as surface flows or as intrusions at small depths.

Of the many deposits referred by Geijer to this type, Cerro Mercado, Mexico, Barth, Nevada, and Algarrobo, Chile, seem to show especially clear-cut evidence of formation at shallow to moderate depths. Some other deposits cited by Geijer, such as Kiirunavaara, Finland, and Iron Mountain, Missouri, may also belong here.

Geijer considers these ore bodies as magmatic injections, and writes (p. 30) that "although no reliable 'geological thermometer' is present, one thus has very strong reasons to suppose that the crystallization of the typical ore bodies has taken place within a temperature range comparable to that of granite pegmatites, and perhaps even higher."

Other geologists have described as replacement bodies many of the deposits cited by Geijer, and their classification here as

[22] Knopf, Adolph: A Gold-Platinum-Palladium Lode in Southern Nevada. U. S. Geol. Survey Bull. 620, pp. 1–18.

[23] Geijer, Per: The Iron Ores of the Kiiruna Type. Sveriges Geologiska Undersökning, Ser. C., 367, Årsbok 24 (1930), pp. 1–39.

high temperature—shallow depth vein deposits rests on the acceptance of the latter hypothesis. A replacement mineralization of this type on at least a small scale is, however, accepted by all.

The deep-seated equivalent of this type of deposit, as pointed out by Geijer, would be the magnetite deposits of the Port Henry area, New York, where apatite and pyroxene occur as accessory minerals in the ore.

As described by Geijer, the deposits at Algarrobo, Chile, occur in Tertiary volcanics of the character of sodic andesites, and trachytes. In the central part of the field the main mass of the ore-bearing igneous rock is an agglomerate. The ore consists of magnetite (in part martitized) with associated apatite and often a little amphibole. Quite locally the ore is made up of small specular hematite plates that enclose round lumps of a fairly coarse-grained tourmaline rock. The ore forms stock- or dike-like bodies. The alterations in the country rock connected with the introduction of the ore consist of actinolitic amphibole, biotite, and locally scapolite. Some magnetite and apatite are also introduced. Another type of alteration has resulted in aggregates of tourmaline, quartz, and hematite. Quite exceptionally, bodies of martitized magnetite appear also in this association. The agglomerates are interpreted as having formed at a very shallow depth, and are of a character to be expected in the sub-structure of a volcanic edifice of andesitic and trachytic character, when its nature has been that of a line or fissure eruption rather than a "central" volcano.

At Cerro Mercado,[24] Mexico, the magnetite (martite) ore deposits occur in brecciated Tertiary volcanics comprising latite and rhyolite lavas and tuffs. At an early stage of mineralization, magnetite with minor calcite was introduced, followed by apatite and diopside. The diopside is found largely as a replacement of the country rock. Augite is a common alteration product in the wall rock of the ore deposits. Typical epithermal types of mineralization, such as porcelain-like silicification of rhyolite and the formation of sepiolite, are also present. Foshag

[24] Foshag, W. F.: Mineralogy and Geology of Cerro Mercado, Durango, Mexico. Proc. U. S. Nat. Mus., vol. 74, art. 23, pp. 1–27, 1928.

favors the hypothesis that the magnetite mineralization formed as a replacement of the enclosing rocks by iron-bearing solutions. He calls attention to certain similarities between these deposits and those at Barth, Nevada, and Twin Peaks, Utah.

At Barth, Nevada,[25] compact hematite with a little disseminated apatite occurs in a Tertiary andesitic lava flow, and shows anastomosing veins in the brecciated footwall. Clusters of apatite radiate from the angles of the andesite fragments. Phlogopite has been formed in the wall rock, and calcite seems also to be developed as the ore is deposited. It is probable that much of the original ore was magnetite. Jones ascribes the origin of the deposits to replacement by hydrothermal solutions at temperatures which may have been between 200° and 300° C.

Hsieh [26] describes contact-metamorphic and hydrothermal iron-ore deposits in Southern Anhui and classifies them as hypothermal to pneumatolytic, mesothermal, and epithermal. All belong to the same period of mineralization. Those of the southern Tangt'u district are particularly interesting here. Ore veins of massive hematite and well crystallized specularite occur in shale and volcanic breccias associated with bodies of dioritic porphyry. In addition to quartz grains, a great number of small apatite grains occur with the ore, and there is an intimate mixture of chalcedony containing many apatite crystals. The country rock shows four types of alteration:—silicification, sericitization, alunitization, and kaolinitization. Silicification, as a microfelsitic aggregate of quartz, is the most important feature. All the alterations are attributed to hydrothermal alteration, and he suggests a mesothermal to epithermal state of the solutions. The intrusions came at the end of the Cretaceous or beginning of the Tertiary.

Cassiterite and Cassiterite-Wolframite.—What appear to be excellent examples of cassiterite-wolframite mineralization at shallow depths are described by Kato.[27] The mineral veins of

[25] Jones, J. C.: The Barth Iron Ore Deposit. ECON. GEOL., vol. 8, pp. 247–263, 1913.

[26] Hsieh, C. Y.: The Iron Deposits of Southern Anhui. Geol. Soc. China, Bull. 10, pp. 317–347, 1930.

[27] Kato, Takeo: The Ikuno-Akenobe Metallogenetic Province. Jap. Jour. Geol. & Geog. vol. 5, pp. 122–133, 1927.

the Ikuno district occur in Tertiary liparite and andesite flows and volcanics. The veins are characteristically of composite character. The Kanajase vein shows four stages of mineralization: (1) tin ore, (2) wolframite-tin ore, (3) chalcopyrite ore, and (4) quartz veins, with gold and silver ores in places. Only the first, and less certainly the second, stages would be interpreted by the present writer as high-temperature. The first stage consists of dense cassiterite, commonly in globular aggregates of radial fibrous crystals, cryptocrystalline or fine-granular quartz, and more or less younger sulphides. Both the tin-stone and quartz seem to have crystallized from the colloidal state. The second stage consists of crystals of wolframite in granular quartz which is associated with cryptocrystalline quartz, well crystallized slender prisms of tin-stone, and scheelite, the latter occurring partly in vugs. Two similar early stages of mineralization are shown in the Daisen vein of the Akenobe mine, which occurs in slate with Tertiary liparite exposed in the vicinity. Here small amounts of bismuth ore, fluorspar and topaz are present in the second stage of mineralization, as well as the wolframite and cassiterite. Kato concludes that the veins of the Akenobe district were formed by superheated hydrothermal solutions, at a temperature near the critical point for water, containing more or less mineralizers; and that the veins of both districts were given off by a magma which has solidified at relatively shallow depth, say two to three kilometers below. They are "cryptobatholithic" in origin.

Graton [28] cites Turneaure as having found that at Llallagua, Bolivia, cassiterite, wolframite, tourmaline, pyrrhotite, and arsenopyrite were deposited in and about a porphyry stock at surprisingly shallow depths.[28a]

Lindgren [29] specifically refers certain cassiterite deposits in rhyolite flows to a high temperature—low pressure origin. He writes (p. 659):

[28] Graton, L. C.: *Op. cit.*, p. 545.

[28a] While this paper was in proof, a description of these deposits, by V. Samoyloff, appeared in ECON. GEOL., vol. 29, 1934, pp. 481–499. It affords much evidence for including the Llallagua-Uncia deposits in the xenothermal group.

[29] Lindgren, Waldemar: *Op. cit.*

The deposits here to be described are found in rhyolite flows and have certain very peculiar characteristics, but so far have no economic importance. They are, it is believed, a sort of exudation deposit, having no deep connections, and have been formed directly from the residual solutions in local shear zones immediately after the consolidation of the flows. They evidently develop at high temperatures and low pressure. It may be recalled that topaz is sometimes found in lithophysae in rhyolite, indicating a retention of certain volatile constituents until consolidation of the flows. The mineral association is wood-tin, and concretionary cassiterite with opal, chalcedony, and specularite, rarely as in Mexico with some wolframite and bismuth minerals; the veinlets have developed colloform structure. Occurrences of this kind have been described from Mexico, Nevada, and New Mexico.

In Nevada [30] tridymite occurs with wood tin, and at one locality in Mexico it is associated with topaz.

Molybdenite-Orthoclase-Quartz.—The Climax molybdenite deposit has been described by Butler and Vanderwilt,[31] and the conclusions given below are from their report.

The molybdenite deposit forms a pipe or stockwork of Tertiary age in pre-Cambrian granite in which schist inclusions and Tertiary dikes are common. It includes (1) a central core in which the rocks have been largely replaced by fine-grained quartz, surrounded by (2) an envelope made up of moderately altered rock cut in all directions by closely spaced intersecting veinlets and grading outward into the unaltered country rock. The molybdenite ore occurs in a zone in the envelope of moderately altered or silicified rock. The rock in the ore zone is composed largely of quartz and secondary orthoclase and is impregnated with pyrite. Small veinlets, mostly less than a quarter of an inch thick, cut the rock in every direction, and in many places it is impossible to find a cubic inch of rock free from them. Some veins in the outer part of the zone consist largely of "blue quartz," a fine-grained quartz colored by minute crystals of molybdenite and containing considerable orthoclase. Characteristically, veins in the ore zone contain molybdenite as fine

[30] Knopf, Adolph: Tin Ore in Northern Lander County, Nevada. U. S. Geol. Survey Bull. 640, pp. 125–138, 1917.

[31] Butler, B. S., and Vanderwilt, John W.: The Climax Molybdenum Deposit of Colorado. Colorado Sci. Soc. Proc., pp. 311–353, 1931.

specks along their margins and some contain small amounts of fluorite. Later than this mineralization are quartz-pyrite veins which in places contain a little chalcopyrite, dark sphalerite, hübnerite, fluorite and, in some at least, topaz. Sericitic veins are most abundant in and near the central core.

The quartz is fine-grained, the molybdenite is rarely large enough for its form to be recognized except with the microscope, and much of it, even when highly magnified, appears only as tiny black specks. The orthoclase of the veinlets is fine-grained, and the secondary orthoclase is finely granular. Topaz is widespread, but everywhere in microscopic crystals.

Butler and Vanderwilt conclude that the minerals at Climax give no very definite evidence as to the temperature of formation but that, like certain other deposits, they would seem to justify the assumption that the deposits were formed under conditions represented by the transitional parts of the hypothermal and mesothermal zones. They further infer that the Climax deposit is genetically associated with a concealed intrusive body whose apex had approached sufficiently near to the surface for the gases liberated from it to escape through the fractured rock and effect the rock alteration and deposit the molybdenite. To the present writer, the association and fine grain of such minerals as molybdenite, topaz, and orthoclase, and the scarcity of other sulphides, suggest a shallow high temperature deposit equivalent to the common deep-seated coarse-grained quartz veins with orthoclase, molybdenite, and accessory minerals.

Scheelite.—The scheelite deposits of the Atolia district, California, have been described by Hulin [32] as an epithermal type formed at relatively low temperature and pressure. Spurr,[33] in reviewing Hulin's report, suggests a high temperature—shallow depth origin, and this seems to the writer a reasonable interpretation.

According to Hulin's description, the deposits are of Middle or Upper Miocene age and consist of fissure veins in quartz

[32] Hulin, C. D.: Geology and Ore Deposits of the Randsburg Quadrangle, California. Calif. State Min. Bur. Bull. 95, 1925.

[33] Spurr, J. E.: Eng. Min. Jour.-Press, p. 463, 1926.

monzonite. The early period of mineralization consists of dense, fine-grained, practically microcrystalline quartz intergrown with equally small grains and crystals of scheelite, grading into coarsely crystalline aggregates of quartz and coarse to medium scheelite with associated pyrite, and a later stage characterized by calcite. Stibnite occurs locally intergrown with the later quartz or cutting it in fractures. In one part of the district a phosphate, probably apatite, is present.

Tourmaline-Cherty Quartz or Jasperoid.—In the southern portion of the Oquirrh Mountains, Gilluly [34] has described hornfelses of contact-metamorphic origin adjacent to small intrusive bodies, and widespread jasperoid bodies replacing limestone along fissures and bedding surfaces without direct relations to exposed igneous masses. These jasperoid masses he interprets as formed by deposition of colloidal silica, accompanied by tourmaline, apatite, zircon, and calcite. Shrinkage openings were perhaps locally filled by colloidal silica, barite, and stibnite. Gold and cinnabar occur in and associated with jasperoid at Mercur, and silver and silver-lead with jasperoid near Mercur and on Lion Hill.

In the Oregon Cascades [35] there is a structural line along which several small areas of hypabyssal intrusion and associated mineralization occur, formed at shallow depth in Tertiary lavas. In all these localities there is more or less tourmalinization of the andesitic volcanics and local tourmaline-bearing quartz veinlets. Tourmaline-epidote, tourmaline-sericite-specularite, and epidote-chlorite hornfelses have all been formed. Locally there are massive bodies of cherty quartz and tourmaline-cherty quartz replacing the volcanics. An auriferous base-betal mineralization follows this early tourmalinitic stage.

Auriferous tourmaline-bearing quartz veins in which the quartz is generally in a massive or cryptocrystalline form have been described by Ignatieff [36] in andesite of Tertiary age in Panama.

[34] Gilluly, James: Geology and Ore Deposits of the Stockton and Fairfield Quadrangles, Utah. U. S. Geol. Survey, Prof. Paper 173, pp. 97–101, 1932.

[35] Buddington, A. F., and Callaghan, Eugene: (In press).

[36] Ignatieff, A.: The Gold Reefs at Remanee Mine, Panama. Mining Magazine, London, vol. 44, p. 155, 1931.

The jasperoid masses at Ely, Nevada, containing considerable pyrite and in places chalcopyrite, have been described by Spencer [37] and referred to a mesothermal range of temperature (200°–350° C.). This jasperoid appears to have formed at somewhat lower temperatures than the tourmaline facies and, although generally consisting of quartz, is composed in part of chalcedony.

Tourmaline-Chalcopyrite.—The Braden mine, Chile, as described by Lindgren and Bastin,[38] affords an excellent example of tourmaline-chalcopyrite mineralization at not great depths. The following pertinent points are abstracted from their paper.

Three periods of mineralization and three periods of igneous intrusion are represented. The first period of mineralization took place in fractured andesite porphyry and is represented by the development of magnetite in cloud-like masses, followed by tourmalinization and sericitization generally accompanied by tourmaline. Brecciated andesite porphyry may be largely replaced by tourmaline. Quartz veins carrying tourmaline, pyrite, and chalcopyrite are also present. Following this came the formation of the Braden cylindrical vent through explosive shattering and its subsequent filling with tuff. The periphery of the vent was also greatly shattered and crackled, and in this zone during the second period of mineralization quartz, tourmaline, pyrite, and chalcopyrite were deposited. Next came the intrusion of dacite and latite, forced upward in part as an intimately brecciated mass. This intrusion was in turn followed by tourmalinization without sulphides. Sulphide mineralization of great variety followed at a later stage and at lower temperature ranges. Lindgren [39] states that the mineralization of the Braden mine probably took place at a depth of about 4000 feet.

The chalcopyrite-tourmaline deposit at the Cactus Mine, Utah, described by Butler [40] may also belong to this group. McLaugh-

[37] Spencer, A. C.: The Geology and Ore Deposits of Ely, Nevada. U. S. Geol. Survey, Prof. Paper 96, pp. 51, 62–64, 1917.

[38] Lindgren, W., and Bastin, E. S.: The Geology of the Braden Mine, Rancagua, Chile. Econ. Geol., vol. 17, pp. 75–99, 1922.

[39] Lindgren, Waldemar: *Op. cit.*, p. 685.

[40] Butler, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah. U. S. Geol. Survey, Prof. Paper 80, pp. 172–178, 1913.

lin [41] writes:—"Deposition at high temperature is clearly indicated by tourmaline and specularite. . . . Depth of formation cannot be closely estimated but was certainly moderate or even shallow rather than deep." The mineralization occurs in a pipe of brecciated monzonite forming a stock intrusive in Tertiary volcanics. The spaces between the fragments of the breccia are partly or entirely filled by ore minerals and gangue. The tourmaline is abundant, and occurs particularly as aggregates radiating outward from the breccia fragments and generally inclosed in later minerals. Sericite and tourmaline occur as alterations of the breccia fragments. The principal metallic minerals are pyrite, chalcopyrite, and hematite, and the common gangue minerals are quartz, siderite, anhydrite, and barite. A little rutile, apatite, tetrahedrite, bornite, galena, and cosalite are found.

Miscellaneous.—The writer has not searched the literature extensively but is certain that many examples of high temperature —shallow to moderate depth mineral associations may be found there, although probably in most cases of no particular economic importance. A few will be noted.

Knopf [42] describes two types of tourmaline-quartz veins, one carrying pyrite, sphalerite, galena, tetrahedrite, and chalcopyrite, another carrying gold and coarse microcline. Chalcedonoid quartz is associated with the sulphide veins, and both types were formed later than granite porphyry dikes which show a spherulitic groundmass. A cinnabar deposit also occurs. All the deposits are thought to have formed at or near the end of Jurassic time. Estimates of depth are not given.

In the Bohemia district,[43] Oregon, is found a vein with cherty quartz, radiating fibrous johannsenite (commonly a contact-metamorphic mineral), albite, adularia, pyrite, and specularite; also veinings of magnetite and epidote. In the Berlin [44] mining dis-

[41] McLaughlin, D. H.: *Op. cit.*, p. 568.

[42] Knopf, Adolph: Geology and Ore Deposits of the Rochester District, Nevada. U. S. Geol. Survey, Bull. 762, pp. 51–54, 1924.

[43] Buddington, A. F., and Callaghan, Eugene: (In press).

[44] Smith, Warren S.: Petrology and Economic Geology of the Skykomish Basin, Washington. Sch. of Mines Quar., vol. 36, pp. 154–185, 1915.

trict, Washington, the Mona vein shows chalcopyrite and sphalerite, with apatite in considerable amounts.

The tourmaline-cinnabar veins of the Mazatzal Mountains, Arizona, described by Lausen,[45] afford a most interesting example of the association of two minerals generally assumed to have been deposited under widely separated depth conditions. "Intergrowths of tourmaline, quartz, and the ferruginous carbonate occur and are practically contemporaneous as regards time of deposition. A later generation of quartz and tourmaline cuts the carbonates, and this is followed by cinnabar that cuts all pre-existing minerals and replaces both quartz and carbonate." Lausen concludes that the most reasonable assumption is that the deposits are of Tertiary age and formed at a depth of 2000 feet or less. He further suggests that the formation of tourmaline is not invariably indicative of former high temperature and great depth or pressure. Cinnabar in association with tourmaline and sericite is described by Knopf[46] from the Rochester District, Nevada, and cinnabar with auriferous tourmaline-jasperoid occurs in the Mercur district, Utah.

In the Beaver Lake district, Utah, Butler[47] has described lavas (quartz latite) of probable Tertiary age replaced by quartz and andalusite with associated muscovite. He notes (p. 82) that "conditions in the Beaver Lake district do not indicate that the lavas were deeply buried, and it seems probable that high pressure is not essential to the formation of andalusite." In this connection may be mentioned the dumortierite deposits with associated andalusite of the Rochester District, Nevada, and the andalusite deposits at White Mountain, California, although since the published descriptions do not give an adequate basis for judgment as to depth of formation, they may have been formed at moderate depth.

PRINCETON UNIVERSITY,
PRINCETON, N. J.

[45] Lausen, Carl: Tourmaline-Bearing Cinnabar Veins of the Mazatzal Mountains, Arizona. ECON. GEOL., vol. 21, pp. 782–791, 1926.

[46] Knopf, Adolph: Geology and Ore Deposits of Rochester District, Nevada. U. S. Geol. Survey, Bull. 762, p. 53, 1924.

[47] Butler, B. S.: *Op. cit.*

REVISION OF STRUCTURE AND STRATIGRAPHY OF THE ASPEN DISTRICT, COLORADO, AND ITS BEARING ON THE ORE DEPOSITS.[1]

JOHN W. VANDERWILT.

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INTRODUCTION AND ACKNOWLEDGMENT

THE old proverb that there are at least two sides to every question applies to the interpretation of the economic geology of the Aspen district. Spurr [2] has presented one interpretation, so well known that it need not be reviewed. An earlier interpretation was published by Emmons,[3] but has not since been referred to. Emmons' interpretation is supported by Mr. D. P. Rohlfing, mining engineer and geologist, who has never published his views, although he came to Aspen before Spurr and has been actively engaged and in touch with the district up to the present time. Spurr emphasizes the existence of bedding faults and their im-

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Spurr, J. E.: Geology of the Aspen Mining District, Colorado. U. S. Geol. Survey, Mon. 31 (with atlas), 1898.

[3] Emmons, S. F.: Preliminary Notes on Aspen, Colorado. Colo. Sci. Soc. Proc., vol. 2, pp. 251–277, 1885–87.

portant influence on deposition of ore, but Rohlfing maintains that there are no bedding faults and that the ore is localized where crosscutting faults intersect certain sedimentary contacts. Rohlfing's view has gained some favor among mining men and geologists to whom he has presented his views and the evidence that supports them. In the fall of 1933 the writer spent about five weeks in the district with the express purpose of reviewing the facts in the light of our present knowledge of geology in Colorado. Rohlfing made available numerous cross-sections and mine maps showing the geology, explained his views in detail to the writer, and guided him through the labyrinth of workings to examine the evidence. The work has been done as a part of the co-operative program of the U. S. Geological Survey with the State of Colorado and the Colorado Metal Mining Association.

In the course of the study, certain details of stratigraphy worthy of description were noted. In order to give a more complete picture of the structural setting of the district, the regional structure as it was observed during past seasons in a study of the Snowmass Mountain area in the Elk Mountains to the west is also reviewed.

Location.—Aspen is in the west-central part of Colorado at an altitude of about 8,000 feet in the valley of Roaring Fork, a tributary of the Colorado River. The district is on the western flank of the Sawatch Range, and can be reached the year round from the north and west by way of Glenwood Springs, both by highway and railroad. It is accessible from the east and south in summer by the Independence Pass highway.

GENERAL GEOLOGY.

The principal geologic features pertinent to this paper are only briefly reviewed, as they are described in sufficient detail in Spurr's monograph, cited above.

The formations in the district consist of pre-Cambrian gneiss and granite, common to essentially all of the Sawatch Range, and sedimentary rocks of Paleozoic, Jurassic, and Cretaceous age.

The Mesozoic beds lie just west of the limits of mineralized zones, and will not be considered further. The general stratig-

raphy of the Cambrian, Ordovician, Devonian, Mississippian, and lower one hundred feet of the Pennsylvanian formations, together with the changes in terminology and subdivision of formations made in recent years by various workers on the eastern side of the Sawatch Range, are shown in Fig. 1 *A* and *B*.

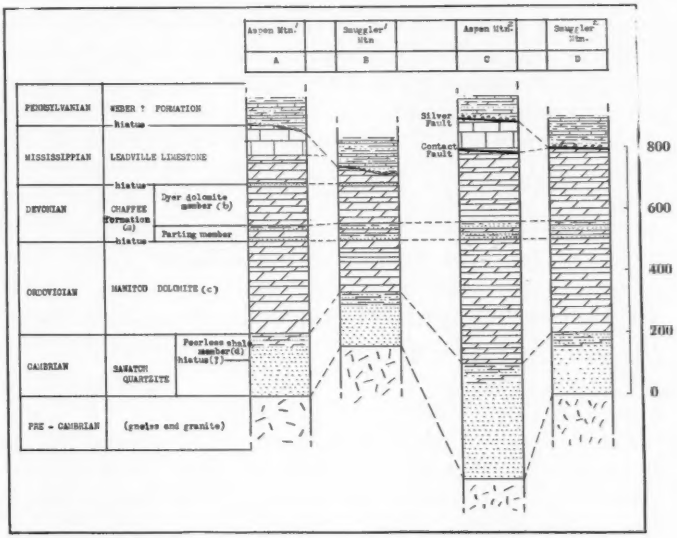


FIG. 1. Principal features of the stratigraphy of the Aspen district. Columns *C* and *D* illustrate interpretations described by Spurr; *A* and *B* show the revisions and other changes described in this paper, 1. Thickness of formations by D. P. Rohlfing. 2. Thickness of formations by J. E. Spurr.

(*a*) Kirk, E. (Introduced term "Chaffee formation.") The Devonian of Colorado. Amer. Jour. Sci. (5), vol. 22, pp. 229–230, 1931.

(*b*) Behre, Chas. H., Jr. (Introduced term "Dyer dolomite," member of Chaffee formation.) The Weston Pass Mining Districts, Lake and Park Counties, Colo. Colo. Sci. Soc. Proc., vol. 13, No. 3, p. 60, 1932.

(*c*) Kirk, E. W. (Correlation with Ordovician of central Colorado.) *Op. cit.*, p. 222.

(*d*) Behre, Chas. H., Jr. (Introduced term "Peerless shale," member of Sawatch quartzite.) *Op. cit.*, p. 58.

Fig. 1 also summarizes the revisions of stratigraphy and the interpretation of structure which excludes bedding faults.

In the Aspen district nearly all metal production has come from two horizons, (1) on Smuggler Mountain along or near the contact between dolomite and overlying shaly members of the Pennsylvanian formation, and (2) on Aspen Mountain along or near the contact between the dolomite and limestone members of the Leadville (Mississippian) formation. The Pennsylvanian formation, as a whole, will not be described because its stratigraphy is not sufficiently well known and it has not been of economic importance except at its lower contact. The horizons below the Mississippian have not been productive, but they have not been adequately prospected. Since they have been of economic importance in other areas, including the Leadville and Redcliff districts, they are of interest in all mineralized areas. These facts, together with the revised interpretation of structure and stratigraphy presented in this paper, suggest that the older formations in the Aspen district deserve further consideration as to ore possibilities.

Revision of Stratigraphy.

Certain local structural features and stratigraphy are so intimately related that the two cannot be kept entirely separate. Regional and local structure are, however, described separately in later paragraphs.

Devonian-Mississippian Boundary.—This boundary has for many years constituted a problem of Colorado geology. In most areas characteristic Devonian and Mississippian fossils were recognized, but the base of the Mississippian was not accurately identified owing to scarcity of fossils at critical horizons. In recent years a sandy bed or zone has been regarded as the base of the Mississippian; it was first described by Gibson [4] in the Redcliff district. Behre [5] later described the horizon in the Leadville

[4] Crawford, R. D. and Gibson, Russell: Geology and Ore Deposits of the Redcliff District, Colorado. Colo. Geol. Survey, Bull. 30, p. 38, 1925.

[5] Behre, Chas, H., Jr.: Revision of Structure and Stratigraphy of the Mosquito Range and the Leadville District, Colorado. Colo. Sci. Proc., vol. 12, No. 3, pp. 38, 39, 1929.

district, and emphasized its continuity even though an inconspicuous horizon. Subsequently Johnson,[6] who studied Paleozoic formations along the northeast flank of the Sawatch Range and around to the west side, including the Aspen district and areas to the south, found the zone in virtually every section examined. Since it is such a persistent horizon with sandstones, interformational breccia, and locally shale, it has been regarded as the probable boundary between Mississippian and Devonian. Even though this correlation could be questioned because of lack of fossil evidence, the sandy zone clearly constitutes a useful horizon marker.

In the Aspen district also the sandy zone is overlain and underlain by dolomite. Numerous outcrops were found but complete sections are not numerous. The best are under Castle Butte at the south end of Tourtelotte Park, and along the old wagon road in Spar Gulch on Aspen Mountain. On Aspen Mountain the interval between the base of the sandy zone and that of the massive limestone is 83 to 90 feet. At Castle Butte the following section was measured:

	feet
Massive (Leadville) limestone, thickness estimated	70.0
Dolomite	1.5
Limestone	3.0
Dolomite	16.5
Limestone	11.0
Dolomite	20.5
Dolomite—with chert	21.5
Sandy zone	8.0

The sandy zone consists of one or more thin (3–6 inch) beds of sandstone in the dolomite, which itself may be sandy. Above the sandy horizon there is an interval of dolomite 15 to 20 feet thick, with numerous nodules and lenticular stringers of black chert. This chert is so characteristic that underground it constituted a distinct aid in locating the inconspicuous sandy horizon. The latter may also be identified underground by a slight widening, due to sloughing, of drifts or crosscuts that penetrate it.

[6] Johnson, J. Harlan, personal communication. See also Lovering, T. S. and Johnson, J. H.: Meaning of Unconformities in Stratigraphy of Central Colorado. Bull. Am. Assoc. Petr. Geol., vol. 17, pp. 366, 367, 1933.

The dolomite above the sandy zone is dark gray, dense, and thin-bedded; lithologically it cannot be distinguished from the dolomite below, and possible chemical differences were not investigated.

The contact between dolomite and limestone [7] is of particular interest and importance because much ore has been localized there, and because it has been interpreted as the "Contact fault." This contact was, therefore, studied in detail and the following features were noted: (1) the contact is uneven, and devoid of breccia except near cross-breaking faults; (2) the limestone, through a thickness of 1 to 2 feet immediately above the contact, is marked by cavities lined with scalenohedrons of calcite; (3) the contact may be either sharp or gradational. In some places it was readily followed in mining, but in others, owing to a gradual change from dolomite to limestone through a zone 5 to 20 feet in thickness, it was difficult to recognize.

The limestone overlying the dolomite is of medium to fine grain and essentially massive from top to bottom. Both texture and massive structure aid in distinguishing it underground from the dolomite, which is invariably fine-grained and generally shows bedding. Fresh fractured surfaces of limestone underground are readily recognized by reflections of light from the cleavage surfaces of relatively large calcite grains scattered through the rock.

Beds of dolomite are present in the lower 20 to 40 feet of the limestone (Fig. 2). This is the rock claimed by Spurr to have been dolomitized by solutions related to sulphide mineralization, but the same relationship [8] is found on Cement Creek, 40 miles to the south, and at Glenwood Springs, 45 miles to the northwest, where there has been no sulphide mineralization. This feature is general in its occurrence and not peculiar to the Aspen district, and it is, therefore, a feature of the normal stratigraphic succession.

[7] In this paper the terms limestone and dolomite are used in their correct meaning. Acid (dil.—3: 1–HCl) tests were made to differentiate the two in the field.

[8] Vanderwilt, John W. and Fuller, N. C.: Correlation of Colorado Yule Marble and Other Early Paleozoic Formations on Yule Creek, Gunnison County, Colorado. Colo. Sci. Soc. Proc. (in press).

The contact between the Pennsylvanian and the Mississippian at Aspen has also been described as a bedding-fault contact (Silver fault in Fig. 1). This contact is easily recognized in west-central and southwestern Colorado because of the contrast between the Pennsylvanian black shales with interbedded thin strata of dolomitic limestone, and the dense hard dolomite or limestone of the underlying formations. It is marked throughout the

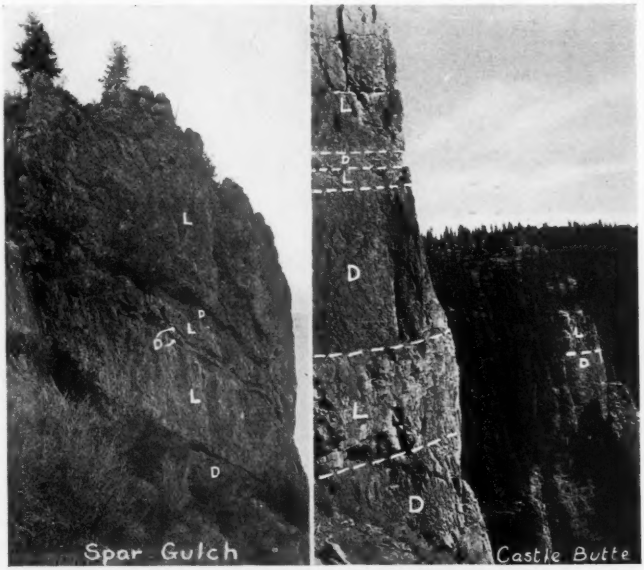


FIG. 2. Dolomite beds in the lower part of the Mississippian (Leadville) limestone. *D*, dolomite; *L*, limestone.

Aspen district by a conglomerate from a few inches to several feet thick, that consists of rounded chert fragments and a few fine-grained quartzite pebbles in black shale. Similar conglomerate is found at this horizon on Treasure Mountain, in the Elk Mountains about 20 miles to the southwest, and also in the San Juan Mountains, where it constitutes the base of the Molas

formation and has been described recently by Burbank.[9] The conglomerate marks an unconformity which is a very uneven surface throughout much of the Aspen district, particularly where it is underlain by limestone. Brecciation is lacking along the contact except in proximity to cross-breaking fractures and faults, and nowhere could any displacement be recognized. In any single exposure, no angularity between the two formations is evident, but detailed measurements of the Mississippian (Leadville) limestone show that its upper member thins gradually northward and wedges out somewhere under the valley of Roaring Fork, thus suggesting that the hiatus is an unconformity.

STRUCTURE.

Regional Structure.—The Aspen district occupies part of a zone of regional deformation, which must be considered briefly before the more local features can be understood. The Castle Creek fault, to which all other structures in the district are related, is duplicated in almost every detail by the Elk Mountain fault in the Elk Mountains 15 miles to the southwest. Both faults flank the Sawatch Range uplift and are nearly parallel for many miles, but they join south of Glenwood Springs and continue for many miles to the northwest along the margin of the White River Plateau (Fig. 3). The faults, as shown in this figure by the generalized cross sections, are involved in disturbed zones marked by monoclinal folds, reverse or high-angle thrust faults, low-angle thrust faults, overturned strata, and closely folded beds. These disturbed zones have a number of characteristic features, the most important of which are:

(1) the disturbed zone is extremely narrow as compared to its length;
(2) the local features are dependent on the curvature along the strike of the zone;
(3) the beds are relatively undisturbed both east and west of the disturbed zone;
(4) the disturbed zones flank areas of important uplift on the east.

[9] Burbank, W. S.: Revision of Geologic Structure and Stratigraphy in the Ouray District of Colorado, and its Bearing on Ore Deposition. Colo. Sci. Soc. Proc., vol. 12, No. 2, p. 161, 1930.

At Aspen, the disturbed zone is less than 1 mile wide, whereas in the Elk Mountains its width in places is 3 miles. Hills [10] described the structure as continuous with the Uinta Mountains in the extreme northwest corner of Colorado. Burbank [11] has mapped the continuation of Elk Mountain fault zone from

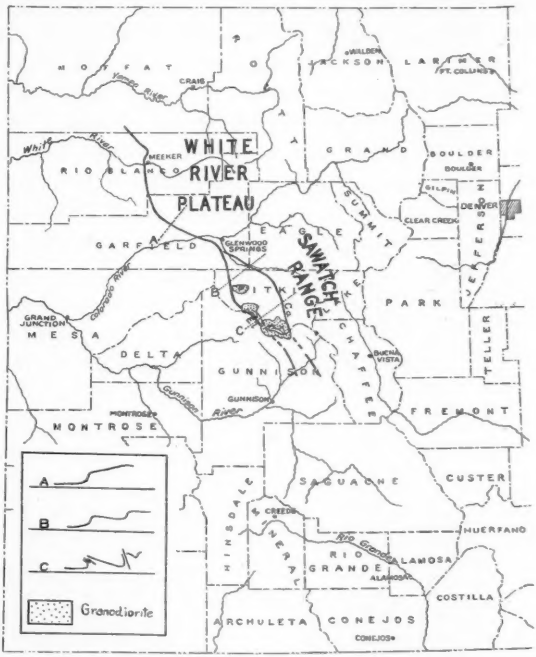


FIG. 3. Relation of Castle Creek (*Ca*) and Elk Mountain (*El*) fault zones to the Sawatch uplift and White River Plateau. Cross sections are generalized and diagrammatic as to scale. The town of Aspen is located in Pitkin County, near intersection of cross-section C and Castle Creek fault.

Crested Butte Quadrangle south across the valley of Gunnison River. In Fig. 3 only that part of the structure examined by the writer is shown.

[10] Hills, R. C.: Orographic and Structural Features of Rocky Mountain Geology. Colo. Sci. Soc. Proc., vol. 3, p. 409, 1889–90.

[11] Burbank, W. S. New geologic map of Colorado.

The relation of curvature of the structure to local features is shown at, and immediately northwest of Aspen. The Castle Creek fault along its southern part is steep, with overturned beds on the west, but northward where its trend changes to northwest, the dip and the total displacement of the fault decrease. Farther northwest, the structure is a monoclinal fold. Similarly the Elk Mountain structure south of Glenwood Springs is a vertical monoclinal fold, but at the town, where it curves westerly, the dip of the limb is only 40° to 60° westerly; farther northwest the limb is again vertical. On the whole, thrust-faulting and large vertical displacements are more in evidence opposite the Sawatch Range than on the flank of the White River Plateau.

The lack of important folding or faulting both east and west of the main zone of disturbance is evident in the field. On the concave or westward side of the zone, southwest of Glenwood Springs and also southwest of Aspen, there is in each place a broad, gentle anticline; otherwise the beds do not reflect the faulting and folding found near-by to the east and north. East of the fault zones, on the northwest flank of the Sawatch Range, small faults with easterly strike have been found.[12] The pattern of these faults has not been fully worked out, and their relation to the regional features is not known, but their position suggests a possible origin due to differential movement between the Sawatch Range and White River Plateau uplifts.

The foregoing brief descriptions suffice to show that the structure at Aspen is a small part of a much larger one and cannot therefore be adequately explained by local disturbances. The close folds and thrust faulting have in the past been attributed to forces originating from the large intrusions found in the Elk Mountains. The distribution of these intrusions (Fig. 3) is clearly controlled by the regional structure. In a detailed study [13] of the intrusive masses, it was found that they cut across the

[12] Stark, T. J.: Personal communication. Lovering, T. S.: Personal communication.

[13] Vanderwilt, J. W.: Report of Snowmass Mountain Area. U. S. Geol. Survey. In preparation.

disturbed zone without affecting it or the sedimentary formations for more than a few thousand feet from their contacts. Tangential forces have become the conventional explanation of mountain structure, but within the exposed vertical limits of the regional structure described above there is little or no direct evidence of such forces; on the other hand, both of the large vertical displacements, as well as the zones of more highly disturbed formations, can be explained readily by vertical movements of the White River Plateau and the Sawatch Range.

Local Structure.—The dominant structural feature of the Aspen district is the Castle Creek fault which, as shown above, is part of a larger regional structure. This fault dips steeply to the east, and on its east side pre-Cambrian granite and gneiss are upthrown along a footwall of vertical and overturned Permian and Jurassic beds. The fault trends almost north to a position about west of Aspen, where it turns to a northwesterly direction and is followed for many miles by the valley of Roaring Fork.

Where the Castle Creek fault swings to the northwest, the strike of the Paleozoic formations that lie on the flank of the Sawatch Range turns to the northeast. Thus the lower Paleozoic formations that crop out along the hanging wall of the Castle Creek fault on Richmond Hill, 3 miles south of Aspen, diverge from the fault as they are traced northward, so that at Aspen the fault and eastern edge of the Paleozoic beds are about a mile apart. At Aspen a sharp syncline and an anticline, with axes that trend and pitch to the north, lie between the Castle Creek fault and the eastern edge of the lower Paleozoic formations. The anticline lies adjacent to the fault and is rather poorly defined in places where the crest is eroded down to the granite; but it is quite evident where the Castle Creek fault enters the valley of Roaring Fork and sedimentary formations are present.

The syncline is well developed on Aspen Mountain. Here the east limb dips about 45° westerly at the surface but in depth it steepens to vertical and is even overturned in places. The bulk of the ore in this locality was produced along this steeply dipping limb. The syncline plunges under Roaring Fork valley, but how

far it continues is not known. The mine workings on Smuggler Mountain are on the northward continuation of beds that form the east limb of the Aspen Mountain syncline, but whether the syncline itself continues as far north as Smuggler Mountain is not known, for although mine development extends down the dip of the beds for over a thousand feet below the bottom of the valley, the local dip of 40° to 50° remains uniform.

Numerous faults cut the structures described above. One set is approximately parallel to the axes of the folds and a second set with east or northeast strikes intersects the folds at 45° to 90°. Those of the second set can be referred to as cross-faults, since some of them cut both Castle Creek fault and the axis of the syncline. On Aspen Mountain these cross-faults, with a few exceptions, have nearly vertical dips, whereas on Smuggler Mountain they dip 35° to 40° southwest. Their footwalls have as a rule moved upward relatively, and the amount of displacement ranges from a few feet to more than 200 feet. An important feature of these faults, especially in relation to ore deposition, is the brecciation or shattering of their walls. In many places the rock is broken throughout zones fully 50 feet wide without any clean-cut fissures to mark the break. The width of the fracture zones and the amount of shattering are not criteria from which it is possible even to surmise the amount of displacement. Wide brecciated zones are found where the displacement is negligible as well as where the movement was relatively large. The actual movement can be determined only where it is possible to recognize the offset of beds.

This summary of the principal local structural features is necessarily brief. For further detail the reader is referred to Spurr's monograph and atlas. The more important features have been given because they have a bearing on the plausibility of Spurr's theory of large bedding faults. The general relationships may not actually disprove, but neither do they call for, large displacement parallel to bedding; in fact, it would be very difficult to find a logical place for them in a disturbed zone of which the Castle Creek fault is a part.

BRECCIA.

The breccia found in the district constitutes evidence against the presence of large bedding faults, and since it is so important in the localization of ore, it will be discussed in some detail. Brecciated and shattered rock, so common in the mines of the Aspen district, is usually present in the walls of stopes. Much ore consisted of sulphides cementing broken rock. Occurrences of fractured dolomite rock, cemented by either calcite or white dolomite but devoid of sulphides, are plentiful. Spurr describes breccia parallel to sedimentary contacts and regarded it as evidence of important displacement. Reference has already been made to the shattered character of the rock along fracture zones or cross-faults. It is also common parallel to bedding, particularly in dolomite, although not continuous for great distances in a given stratum. The two types of breccia, those related to cross-faults and those related to bedding, will be considered briefly.

Breccia Related to Cross-Faults.—The forces responsible for brecciation were such that in places wide zones of rock were shattered without producing any material displacement. As a rule fault gouge is lacking or unimportant. In places a breccia well developed on one level cannot be found on lower levels. On Smuggler Mountain the beds strike N. 45° $\pm$ E., dip 50° NW., and are cut by faults that strike N. 45° W. and dip 30° SW. Displacement ranges from nothing to more than 200 feet, and the fault is commonly a much shattered zone more than 100 feet across. Invariably the beds in the footwall are offset to the west, but whether this is the result of strike or dip slips has not been determined. At the intersection of such cross-faults with the contact between Devonian or Mississippian dolomite and Pennsylvanian shaly limestone, pronounced brecciation resulted. The relationship is shown diagrammatically in Fig. 4. Particular emphasis is placed upon these cross-faults and the accompanying brecciation because (1) with sedimentary contacts, some of the most important ore bodies were found along their intersection and (2) the breccias have been cited as evidence for the existence of bedding faults. As shown in Fig. 4, brecciation along the

dolomite-shale contact diminishes away from the cross-fault. The ore and breccia are virtually co-extensive. Neither brecciation nor ore, however, are continuous along the contact between adjacent parallel cross-faults except locally where faults are close together. Many of these intervals devoid of breccia and barren of sulphides are accessible and were examined by the writer in

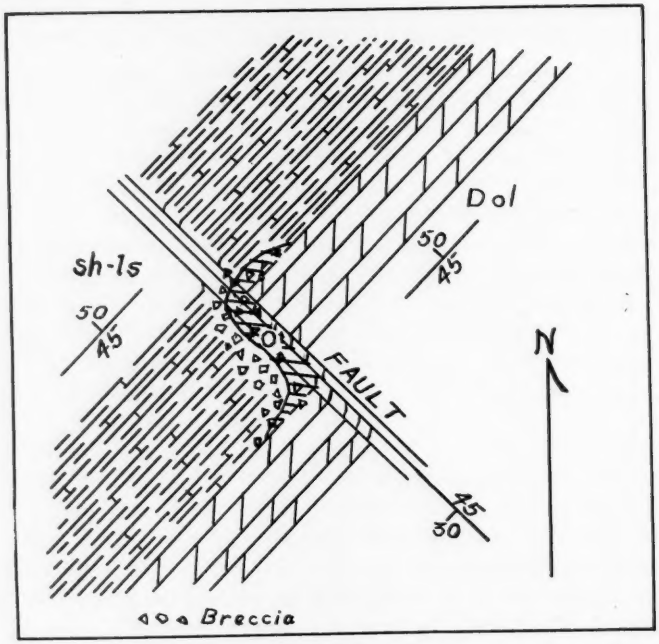


FIG. 4. Ground plan showing diagrammatically the breccia produced by cross-faults on Smuggler Mountain and the relative position of the ore zone (*O*) to breccia, fault, dolomite (*Dol*)—shaly limestone (*Sh-ls*) contact.

the workings under Smuggler Mountain. The obvious relation of this breccia to the cross-faults refutes the idea that they resulted from faulting parallel to bedding.

Breccia Parallel to Bedding.—Brecciation of dolomite is more

common than that of limestone. A brecciated bed of dolomite in a dolomite formation is a common occurrence, and in places beds of dolomite inclosed in limestone are strongly brecciated without any detectable fracturing of the inclosing beds. Breccias of this kind are less than 6 feet thick, and both in dolomite and in limestone are cemented with carbonate or sulphides. In limestone, the dolomite breccias, cemented with enough sulphides to make ore, have been cited as examples of ore with "mantles" of dolomite and have been regarded as dolomitization related to the mineralizing solutions. The brittleness of dolomite and toughness of limestone are well known, and would readily account for the fact that there is much more dolomite breccia than limestone breccia. At no place could the actual amount of movement represented by these breccias be determined. It is the writer's opinion that the brecciation was caused by shearing stresses produced by the close folding of the formations, and that relative movements amounted to only a few inches. Since brecciation took place along cross-faults where the total displacement was unimportant, the breccia parallel to bedding cannot be accepted as evidence of important movement.

Relation of Breccia to Ore Deposition.—The direct relation of breccia to ore deposits lies in the relatively large percentage of open space through which the solutions can circulate. In the Aspen district the ores consist largely of sulphides that fill open spaces, but important replacement of rock also occurred in places. Since dolomite breccia is more abundant than limestone breccia, dolomite horizons should theoretically be more favorable for the occurrence of ore than limestone beds; however, in places on Aspen Mountain wide-spread disseminations of silver sulphides have occurred in limestone that appears to be free of shattering or brecciation. A similar relationship of sulphides in dolomite was not recognized and would seem to indicate that, unless brecciated, dolomite was less easily attacked by the mineralizing solutions than limestone. The importance of breccia is clearly brought out on Smuggler Mountain, where all the rock is essentially equally resistant to attack by solutions and the ore is virtually confined to breccia. Here the interbedded shales, dolomitic

limestones, and sandstones of the Pennsylvanian (Weber?) formation are more brecciated than the underlying dolomite, and the amount of ore obtained from the dolomite is relatively unimportant.

DOLOMITIZATION AND SILICIFICATION.

Both silicification and dolomitization related to mineralization are found in the district and are described by Spurr. Their true relationship to the ore minerals offers an interesting problem whose solution requires much more patient and detailed scrutiny than the limited time at the writer's disposal has permitted, but even in the brief study made, several relationships have evolved that are worthy of mention.

Silica in two forms was noted:—(1) cryptocrystalline in texture, as chert and (or) jasperoid, and (2) well formed small (1 by 2 mm. or less) quartz prisms. Cryptocrystalline quartz, although it might have occurred in ore taken from the stopes, was not found associated with the sulphides remaining in the walls of the stopes. Quartz prisms, however, are common in the walls of stopes and also in the fractured zones or faults along which mineralization occurred. Limestone from the walls of stopes even where it appears unaltered to the unaided eye, commonly shows quartz crystals when examined under the microscope. In places along faults in limestone, silicification has produced rock which so closely resembles quartzite that its constituent quartz crystals can hardly be recognized without the aid of a lens. In places the leaching of this kind of silicified rock has yielded spongy, almost fibrous mats of crystals that have been mistaken by prospectors for cerussite. The quartz is scattered through the rock with crude veining that is not evident on fresh surfaces, but is quite marked on weathered specimens.

Spurr believed that dolomitization related to ore deposition was widespread and occurred on a very large scale. He believed that much of the secondary dolomite or dolomitized limestone was lithologically indistinguishable from original dolomite, which is a dense dark-gray rock. Examples of such secondary dolomite include the "mantles" found around ore in limestone which, as shown in the foregoing discussion of stratigraphy, in reality rep-

resent localization of ore along and within brecciated beds of original dolomite. Another example of supposedly secondary dolomite lithologically indistinguishable from original dolomite is found over a relatively large area in the Harkins, Jenny Lind, and Mayflower tunnels. In this area the recognition of the sandy horizon that forms the base of the Mississippian formation proves beyond reasonable question that the dolomite is the original rock. The significance of these observations is twofold: (1) it questions the existence, in the Aspen district at least, of secondary dolomite lithologically resembling original dolomite, and (2) a strong element of doubt is thrown on the theory that dolomitization and sulphide mineralization are intimately related. The independence of dolomitization and sulphide mineralization is also supported by the fact that ore in limestone is common. Such ore commands a premium at smelters because of its excellent fluxing properties due to its high content of lime.

Secondary carbonate, although not quantitatively important, is widespread. It occurs as: (1) coarse white carbonate in veinlets and as the matrix cementing dolomite breccia; and (2) medium-grained, gray to white carbonate in the fractured or faulted zones near stopes. A possible third mode of occurrence is that of calcite in scalenohedrons that line cavities in limestone, particularly along the dolomite-limestone contact.

The carbonate ranges in composition from calcite to dolomite, although calcite is more abundant in the first mode of occurrence than in the second. Both the coarse and medium-grained carbonate generally yield microchemical tests for iron, and where weathered have brown, iron-stained surfaces. They differ in that the coarse-grained carbonate is not obviously related to sulphide mineralization, as it commonly occurs at some distance from ore bodies and is free of quartz, whereas the medium-grained carbonate is largely confined to the fractured or faulted zones and as a rule has associated with it the well-formed though small prisms of quartz described above. To determine how much of the carbonate may represent recrystallized limestone and dolomite, if it is possible to do so, would require a painstaking, detailed study. The writer believes that the iron content of the

carbonates indicates, or at least suggests, that they are related to the mineralizing solutions that introduced the ore minerals.

BEARING OF REVISION ON FUTURE OF THE DISTRICT.

The general opinion has prevailed that the Aspen district is mined out, especially at shallow depths. Ore possibilities with deeper mining, even though of decided interest, cannot be considered here. The important ore bodies on Smuggler Mountain were found at the contact of dolomite and overlying Pennsylvanian (Weber?) shaly limestone, and those on Aspen Mountain were found at the contact of the dolomite and overlying limestone —both of which are members of the Leadville (Mississippian) formation (Fig. 1). Those who regard the district as exhausted have supposed that the ore found along these two contacts occurred in contact veins. Although the cross-faults have been known to be important structurally, they have never been regarded as ore channels, and consequently no prospecting has been done along them. Important law suits in which able engineers testified were decided in favor of the group that supported the theory of contact veins, and the view that the contacts were faults further strengthened the theory. Virtually all mine workings are confined to the two contacts, and it cannot be denied that they have been thoroughly tested on Smuggler Mountain and on much of Aspen Mountain. All other contacts were avoided and as a result they have been crossed in but few places by mine workings. According to the interpretation here presented, the ore bodies occur at the intersections of cross-cutting faults and normal sedimentary contacts.

It is quite possible that localization of ore may have occurred at the intersection of these same faults or others and at stratigraphically lower or higher contacts. Similar conditions have been found in other areas and are, therefore, worthy of consideration in the Aspen district. With these conditions in mind, the following horizons deserve attention: (1) the shaly beds of the Cambrian (Sawatch) quartzite, (2) the top, bottom, or inner part of the Parting member of the Chaffee (Devonian), (3) the contact of the Leadville (Mississippian) limestone and overlying

Pennsylvanian shaly limestone, and (4) the tops or bottoms of the porphyry sills in the Pennsylvanian formation.

Mineralization has not been reported from the shaly beds of the Cambrian, but it has been found in the other three horizons listed above. The Parting member, where it is faulted opposite the contact between dolomite and shaly limestone on Smuggler Mountain, has produced some good ore, although operators apparently were not aware of the fault and did not recognize the Parting member. Ore in the Parting member has been found [14] recently in another place on Smuggler Mountain and also in the Midnight Mine, operated by Fred D. Willoughby, on Richmond Hill, three miles to the south of Aspen. The contact between the Mississippian limestone and overlying Pennsylvanian shaly limestone, has supplied considerable ore in Tourtelotte Park but has never been developed to any extent on Aspen Mountain only a few miles to the north, where it therefore offers attractive possibilities to intelligent prospecting. Ore bodies that have produced more than $1,000,000 in silver have been mined from within a short distance of the top of a porphyry sill in the Pennsylvanian formation on Richmond Hill in the Little Annie Mine and in the Midnight Mine. This sill or one like it is found on Aspen Mountain and also on Smuggler Mountain, but has not been prospected where it is cut by faults.

These examples of mineralization along other horizons than those regarded as all-important in the past fully support the theoretical expectations of mineralization based on the revised geology and stratigraphy. It is not to be expected that ore can be developed at all intersections, as some are more favorable than others, and ore-forming solutions have not reached them all. A consideration of the relative merits of intersections will necessitate the taking into account of many factors that are outside the scope of this paper. It is, however, logical to conclude that other contacts, so long as they have not been tested at their intersections with cross-faults, are worthy of serious consideration.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

[14] Rohlfing, D. P. Personal communication.

PRIMARY SILVER MINERALIZATION AT SABINAL, CHIHUAHUA, MEXICO.

PHILIP KRIEGER.

INTRODUCTION.

THE silver district of Sabinal is located in the eastern foothills of the Sierra Madre Mountains of northwest Chihuahua, approximately 11 kilometers west of Sabinal station on the Mexican Northwestern Railroad. It is about 100 kilometers due south of Columbus, New Mexico, and 156 kilometers southwest of El Paso, Texas.

Two distinct types of deposits occur in the district, (1) pyrometasomatic deposits, located along the contact of the igneous intrusive and the sediments, and (2) fissure vein deposits, located in the limestone at distances of 50 meters to a kilometer or more from the igneous intrusive. This study is intended to deal chiefly with the mineralization in the Florencia-Magda vein, from which the bulk of the silver production of the district has been derived.

Mineralization in the Florencia-Magda vein is of interest because of the unusual mineral relationships and because it contains evidence that native silver was deposited from primary, or hypogene solutions. In this respect it resembles the well known occurrences of native silver at Cobalt and South Lorraine in Ontario, and in the Erzgebirge of Saxony, where the silver is generally recognized as being of primary origin. Bastin[1] has described the occurrence of primary native silver ores from the Monte Cristo mine near Wickenburg, Arizona, which likewise show similar features.

Mining is reported to have been carried on intermittently in the district since 1821. The early operations, however, were not

[1] Bastin, E. S.: Primary Native Silver Ores near Wickenburg, Arizona, and their Bearing on the Genesis of the Silver Ores of Cobalt, Ontario. U. S. Geol. Surv., Bull. 735, pp. 131–155, 1923.

extensive, and most of the ore probably came from shallow workings located along the contact of the igneous intrusive and the limestone. American operators became interested in the district near the close of the last century and several companies were organized to exploit the group of contact deposits. These operations were carried on for a period of about ten years and the deposits were worked to a depth of over 600 feet. The ores were

FIG. 1. Sketch map showing location of Sabinal.

chiefly of the lead-silver type, carrying fairly high values in gold and silver. Complete records of the production from these deposits are not available; one of the mines, however, the Adventurera, produced approximately $1,250,000 worth of ore in this period.

The Florencia-Magda vein, with which this study chiefly concerns itself, was not discovered until about 1880. Incomplete

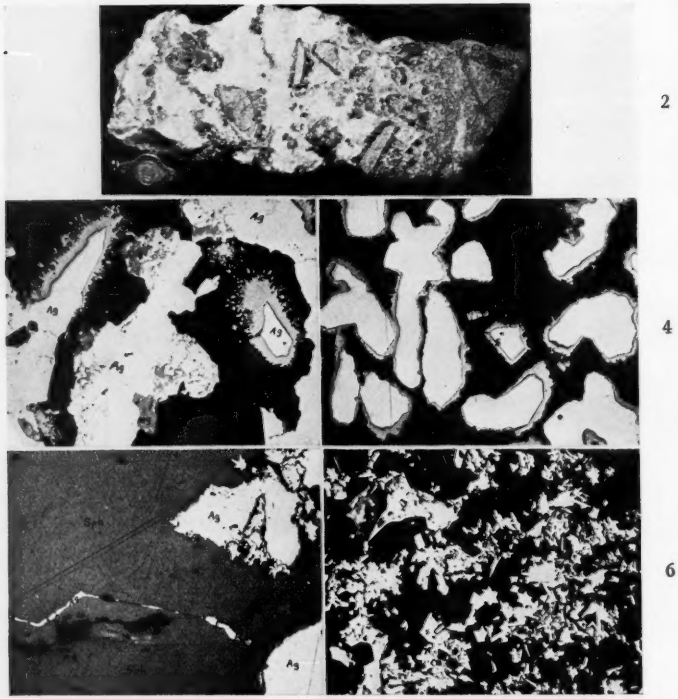


FIG. 2. Angular fragments of altered wall rock in barite with sphalerite and galena deposited around them. Mineralization here has favored the wall-rock fragments.

FIG. 3. Native silver (*Ag*) bordered by arsenides and associated with argentite (*Arg*) and sphalerite (*Sph*). Black, gangue. × 50.

FIG. 4. Granules of native silver surrounded by arsenides, typical of native silver at Sabinal. Black, gangue. × 50.

FIG. 5. Veinlet of native silver in sphalerite and larger areas of native silver associated with stellar-shaped, twin crystals of safflorite. × 50.

FIG. 6. Clusters of rhombic crystals and stellar-shaped, twin crystals of rammelsbergite and safflorite in gangue. Small areas of native silver occur with the arsenides. × 50.

records indicate that the production from this vein has been approximately eight million ounces of silver, half of which was produced between the years 1925 and 1928. It was during these latter years that some of the extremely rich ores were found, and it is authentically recorded that a single carload of 35 tons of ore yielded a smelter return of $91,000.

Acknowledgments.—Sincere appreciation is extended to Mr. Charles E. Stott and Mr. James H. Parker for their enthusiastic co-operation, without which sufficient data and specimens could not have been obtained to complete this study. A visit to the property in the company of these men, during the summer of 1933, afforded an opportunity to observe the field relations and to gain an idea as to the geology of the surrounding area. Mr. S. Lee, manager of the Magda Mining Company, kindly extended the hospitality of the camp during the visit. The writer is also indebted to Professors R. J. Colony and William M. Agar of Columbia University for many suggestions and criticisms in connection with the petrologic studies.

GENERAL GEOLOGY.

The oldest rocks exposed in the vicinity of the mine are a series of Lower Cretaceous sediments consisting of limestone, sandstone and shale, which strike in a northwest direction and dip from 50 to 60 degrees north. These have been intruded by an igneous mass whose mineral composition corresponds to that of an alaskite. The alaskite is believed to have been the source of the mineralizing solutions. Diabase and alaskite dikes also cut the sediments.

The veins in which the silver occurs consist largely of barite, calcite and silica. Although several of them occur in the vicinity, most of the production from this type of deposit has come from the Florencia-Magda vein, which cuts the limestone at some distance from the igneous intrusive. This vein strikes in a general east-west direction and dips from 75 to 85 degrees south. The width varies from a fraction of a foot to five or six feet.

The Sediments.—Adjacent to the igneous intrusive in the vicinity of the Florencia-Magda vein the sediments consist of

thin-bedded, shaly limestone. This series has a thickness of approximately 200 feet. These are overlain by about 600 feet of massive limestone locally called the Sabinal beds. The richest ores have been found where the Florencia-Magda vein has intersected these beds. Above the Sabinal beds are a series of more thinly bedded limestones, shales and sandstones that have a total thickness of at least 700 feet. The youngest beds, or Bufa limestone, are massive and thick-bedded and contain numerous fossil foraminifera identified by Dr. H. N. Coryell, of Columbia University, as *Orbitolina texana,* characteristic of the Lower Cretaceous of northern Mexico and Texas.

One of the most striking features of the sediments is the extent to which they have been affected by pyrometasomatic, or contact-metamorphic processes. Some of the beds have been completely silicified; others have been thoroughly recrystallized with the development of a variety of silication products characteristic of contact metamorphism. In the vicinity of the igneous intrusive the shaly members have been metamorphosed to a dense, flinty hornfels. Large masses of garnet, epidote and diopside are found among the more calcareous members. At a distance of at least 300 feet from the contact, in the Lower Sabinal beds, the limestone has been entirely recrystallized, with the development of innumerable minute crystals of tremolite and scapolite.

Metallic deposits of pyrometasomatic origin also occur along the contact of the alaskite and the sediments. They contain hematite, magnetite, pyrite, galena, sphalerite and small quantities of gold and silver. These deposits are extremely erratic, however, in both distribution and tenor of the ore, and were operated for only a short period during the early history of the district.

The widespread metamorphism and abundant development of complex silication products and metallic minerals suggest that a large quantity of material was introduced into the sediments by emanations from the nearby igneous intrusive.

The Alaskite Intrusive.—The igneous intrusive believed to be the source of mineralization in the district is an alaskite which outcrops about 200 feet west of the Magda shaft. The mass

appears to be a stock extending in a northerly direction, the surface of which is exposed over a distance of approximately a kilometer and a half. It is undoubtedly much larger than the area exposed in the immediate vicinity of the mine would indicate. Small erosional remnants of the same igneous rock, and probably a part of the same mass, are found protruding through the accumulated dry wash of the basin floor between the mine and Sabinal station.

Megascopically the rock is characterized by its very light color, moderately granitoid texture, and the absence of dark colored minerals. A freshly chipped hand specimen shows only quartz and feldspar. On a weathered surface patches of rusty iron oxide and dendritic manganese oxide are evident.

In thin section the rock is holocrystalline and consists largely of quartz and sodaclase, with smaller amounts of orthoclase and muscovite. Injection of end-stage albite into earlier crystallized feldspar has resulted in the formation of what is essentially an injection perthite in some of the specimens observed. Small quantities of magnetite, ilmenite, zircon, rutile and apatite are present as minor accessory minerals. Carbonate is also present in considerable quantity in some of the specimens.

By far the most prominent constituents in the rock are quartz and sodaclase. Muscovite is perhaps next in abundance and orthoclase is present in smaller quantities. The optical properties of the plagioclase correspond more closely to those of albite, although the mineral is not believed to be a pure soda feldspar, but probably contains some potash. A rock of such composition, consisting essentially of quartz and alkali feldspar, and lacking in dark colored ferro-magnesian minerals, would correspond to an alaskite as redefined by Johannsen.[3]

The rock minerals have undergone considerable modification as the result of changes taking place during final consolidation of the magma. The magma appears to have been charged with highly concentrated residual solutions consisting of quartz, albite, carbonate, and probably some volatile gaseous constituents which

[3] Johannsen, Albert: A Descriptive Petrography of the Igneous Rocks, vol. 2, p. 106, 1932.

have acted upon and replaced some of the earlier crystallized products. This is particularly true of the carbonate which, in some cases, has almost completely replaced feldspars and is distributed interstitially throughout the mass of the rock. Albite and quartz are likewise distributed interstitially and around the margins of earlier crystallized minerals. Many of the feldspars are highly sericitized and some areas of a slide show large felted aggregates of the secondary mica which is believed to be a result of the same general process. This is essentially a deuteric process, as described by Sederholm [4] and Colony,[5] and is directly related to the consolidation of the magma itself and not due to outside influence or to the introduction of material from an outside source.

The Florencia-Magda Vein.—The Florencia-Magda vein outcrops a short distance from the igneous intrusive and strikes in a northeasterly direction, at right angles to the strike of the limestone. It dips from 75 to 85 degrees south and has been developed for a distance of approximately 1,000 feet and to a depth of 500 feet.

Although several more or less parallel barite-quartz-calcite veins occur in the vicinity, essentially all the silver produced from this type of deposit has come from this one vein. The richest ore has been derived from the upper 300 feet. Below that the silver content has gradually diminished.

This vein appears to be a typical fissure vein and probably represents an area of weakness along which some movement had taken place prior to the actual vein filling and mineralization. Such movement is indicated by striated vein walls with no apparent indication of movement in the vein material itself, and by angular fragments of wall rock completely enclosed in a gangue of barite. These angular fragments commonly show a rim of metallic minerals, whose deposition appears to have favored the more calcareous wall rock.

[4] Sederholm, J. J.: On Synantetic Minerals and Related Phenomena. Bull. Geol. de Finlande, No. 48, 1916.

[5] Colony, R. J.: The Final Consolidation Phenomena in the Crystallization of Igneous Rock. Jour. Geol., vol. 31, pp. 169–178, 1923.

Vein walls, although irregular, are sharp and well defined except where the vein becomes quite narrow or where shoots or stringers branch away from the main fissure. Although no ore has been found beyond the vein walls, intense alteration of the wall rock adjacent to the vein has been accomplished in some instances. Portions of the limestone have been largely replaced by albite, and sufficient chlorite has developed to give the rock a distinct greenish color. These areas are also strongly impregnated with pyrite, this mineral seeming to favor the wall rock in preference to the vein material for its deposition.

The presence of abundant colloform or banded quartz and drusy cavities, with the walls of the cavities commonly coated with metallic minerals, would indicate that numerous openings existed at the time of vein filling.

GANGUE MINERALS OF THE VEIN.

Barite.—This is one of the most abundant of the gangue minerals and in some instances makes up the greater portion of the vein. It is white, or bluish white, in color and occurs as large masses of thin, platy crystals. Although one of the earlier minerals, the period of its formation extended through at least the beginning of metallic mineralization. Fragments of wall rock with sphalerite and galena deposited around them have been broken and the intervening areas filled with later barite. Under the microscope, fractures in sphalerite can be seen that have also been filled with barite. Quartz replaces barite wherever the two minerals are seen together.

Calcite.—Calcite also occurs in considerable abundance throughout the vein. It is mostly associated with barite, and the two minerals are believed to have been deposited throughout much the same period of time. Deposition of both minerals, however, extended through the early period of metallic mineralization.

Silica.—With the possible exception of barite, silica is perhaps the most abundant gangue material in the veins. It occurs in a variety of forms including euhedral quartz crystals, aggregates of large interlocking quartz grains, intricately banded chalcedonic

material, microcrystalline aggregates, finely feathered chalcedony, and as mixed drusy material lining the walls of cavities. Many of these varieties can be seen in a single slide. In addition, pseudomorphs of quartz or chalcedony after barite and calcite are common.

Colloform banding in the silica is unusually abundant. When viewed in thin sections, however, many of the areas where one would expect to see finely crystalline chalcedony are found to consist of aggregates of crystalline quartz in large interlocking grains, with the colloform banding still preserved in them, suggesting a colloidal origin. Open spaces due to shrinkage of the gel were developed and were later filled with additional quartz and chalcedony. The presence of numerous small grains of pyrite, tetrahedrite and argentite diffused throughout areas of colloform silica would seem to indicate that these minerals were present in the gel-like material before the latter crystallized to its present form. These diffused particles in places conform to the colloform banding of the silica or radiate as stringers from a common center.

Deposition of silica in its various forms followed the deposition of barite and calcite and continued throughout most of the period of metallic mineralization. Replacement of metallic minerals by silica was observed in most of the specimens examined.

Siderite.—This mineral occurs as fairly large masses throughout some portions of the vein, and is generally associated with barite and silica. It is earlier in sequence than silica and probably belongs to the same period of deposition as the barite and calcite.

Fluorite.—Fluorite was found in one specimen from below the 300 level. It occurs as small cubes lining the walls of cavities and is associated with colloform silica and barite. Although it is believed to be related to the period of hypogene mineralization, it is not a common gangue mineral in the vein.

Iron Oxide.—This material is abundant wherever surface waters have had access to the vein, as along open water courses or through vuggy areas. Native silver, in the form of fine wires, and cerargyrite, is associated with it.

METALLIC MINERALIZATION.

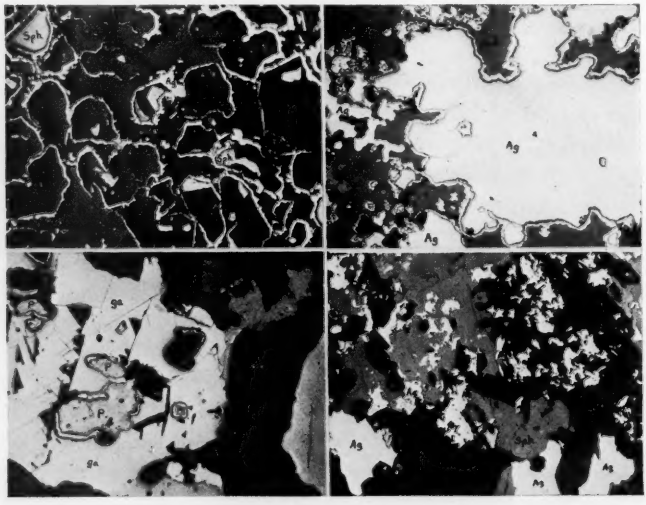
Native Silver.—This is one of the most important of the metallic minerals in the deposit. It occurs chiefly as masses of nodular grains hung together in a dendritic-like pattern and is usually associated with cobalt and nickel arsenides. Other minerals commonly associated with it are sphalerite, galena, barite, quartz, calcite, and rarely argentite. One such mass, consisting largely of native silver, is reported to have weighed 1,800 pounds. Silver also occurs as leaf-like forms in fractures, as small crystal rosettes in vugs, and as fine wire silver. The latter variety generally occurs in highly oxidized areas and is probably of supergene origin.

Examination of many specimens from various parts of the mine show that cobalt and nickel arsenides consistently surround nodular grains of native silver (Figs. 3, 4). It is the presence of these minerals, generally recognized as being of primary origin, and the manner of their occurrence, which afford the strongest evidence for the primary origin of most of the native silver. Additional evidence for such an origin is found in the general mineral assemblage with which native silver is commonly associated. Such minerals as galena, sphalerite, barite, calcite, small quantities of chalcopyrite and tetrahedrite, none of which show any evidence of oxidation when occurring in these mixed masses, all strongly indicate a primary origin for the native silver. The occurrence of cobalt and nickel arsenides and the manner in which they surround native silver are strikingly similar to the occurrence of these minerals at Cobalt and South Lorraine in Ontario, where the native silver is generally recognized as being of primary origin.

Deposition of native silver is believed to have taken place late in the period of metallic mineralization, but before the final deposition of the cobalt and nickel arsenides. Veinlets of native silver penetrating sphalerite clearly show its sequence with respect to this mineral. Some of the silver may have been contemporaneous with the arsenides, but the fact that the arsenides consistently surround native silver would indicate that they formed at a later period.

Native silver of supergene origin is not believed to be entirely lacking in the veins. As previously stated, fine wires of silver occur associated with limonite and calcite in oxidized areas where the vein material has been much decomposed. In these areas the arsenides and other mineral associates are absent, and the occurrence is so generally different from its occurrence elsewhere that the silver here is believed to be due to supergene agents.

Pyrargyrite and Polybasite.—These minerals occur most abundantly along the contact of the vein material and the wall rock.



7 8 9 10

FIG. 7. Calcite grains surrounded by rims of arsenides, associated with native silver (Ag) and sphalerite (Sph). × 50.

FIG. 8. Native silver (Ag) in sphalerite (Sph), surrounded by seams of cobalt or nickel arsenides. Small grains consist of cores of native silver bordered by arsenides. × 50.

FIG. 9. Grains of pyrargyrite and polybasite (P) surrounded by rims of cobalt or nickel arsenides in galena (ga). Gray, gangue. × 50.

FIG. 10. Intimate mixture of native silver (Ag), sphalerite (Sph) and arsenides (small, white crystals) in gangue of quartz and barite (dark gray). × 50.

In a hand specimen the material appears to be entirely homogeneous, but when examined by reflected polarized light it is found to be an intimate mixture of pyrargyrite and polybasite. They usually occur in a gangue of barite, quartz and calcite, and are commonly associated with pyrite, sphalerite and galena. Some specimens also show native silver, chalcopyrite and the arsenides of cobalt and nickel associated with these minerals. In such cases the arsenides border pyrargyrite and polybasite as well as native silver and sphalerite.

Pyrargyrite and polybasite are later than pyrite in sequence but show replacement by sphalerite and by later silica. This would indicate that they were one of the earliest of the metallic minerals to be introduced.

Argentite (or Acanthite).—This mineral occurs through much of the mineralized area and is associated with many of the other metallic minerals as fine intergrowths. Occasionally larger masses of the pure silver sulphide are found. A polished surface of one of the larger pieces showed distinct anisotropism characteristic of the orthorhombic variety known as acanthite, which, as laboratory experiments have shown, forms at a temperature below 180° C.[6] The orthorhombic character of this mineral was further confirmed by an X-ray diffraction photograph kindly taken by Dr. Paul F. Kerr, which was found to correspond with diffraction photographs of silver sulphide taken at a temperature below 180° C. by Emmons, Stockwell and Jones.[7]

This would not necessarily indicate that the mineral was deposited by solutions below this temperature, for the experiments of these workers have shown that silver sulphide may be heated to a temperature greater than 180° C., when it assumes an isometric structure. On cooling, however, the same material will revert to the orthorhombic form. Etch tests on the Sabinal material give no clue as to the original form of deposition.

In most of the specimens studied the silver sulphide is believed to have been deposited by hypogene solutions. It is later in

[6] Emmons, R. C., Stockwell, C. H., and Jones, R. H. B.: Argentite and Acanthite. Amer. Miner., vol. 11, pp. 326–328, 1926.

[7] *Idem.*

sequence of deposition than pyrite and sphalerite and replaces both these minerals. Mixtures of silver sulphide and native silver are in turn surrounded by arsenides of cobalt or nickel, so that it apparently preceded the deposition of the arsenides and may have been slightly earlier than, or contemporaneous with, native silver.

Pyrite.—The formation of pyrite appears to have accompanied the early mineralization and alteration of the wall rock. It occurs as small cubes and irregular grains which clearly show replacement by later metallic minerals and by silica. Although pyrite is a fairly common constituent of the veins, it is far more abundant in the highly altered adjacent wall rock. In the veins it is commonly accompanied by pyrargyrite, polybasite and sphalerite. It is believed to be the earliest of the metallic minerals introduced.

Sphalerite.—Clear, amber-colored sphalerite is found associated with essentially all the metallic minerals and is commonly present in appreciable quantities in masses of native silver. Its period of deposition followed that of pyrite, pyrargyrite, polybasite and galena but is distinctly earlier than native silver and argentite. Angular fragments of altered wall rock embedded in vein material commonly show rims of sphalerite and galena. In such cases the deposition of these minerals appears to have favored the fragments of wall rock in preference to the baritic vein material.

Galena.—This mineral is present in many parts of the vein and is commonly found in a gangue of barite. It is commonly accompanied by sphalerite or is associated with sphalerite where the latter mineral occurs with native silver. Most of the specimens examined show it to be earlier in sequence than sphalerite, although in some instances contemporaneous deposition may have taken place.

Chalcopyrite.—Chalcopyrite was observed only as small grains inclosed in pyrargyrite and polybasite or in sphalerite. Its paragenetic relationship could not be accurately determined, although its occurrence as minute grains in sphalerite suggests unmixing from a solid solution.

Tetrahedrite.—Tetrahedrite is present as isolated grains associated with quartz and barite. It was not seen in contact with

other metallic minerals, so that its sequence could not be determined.

Cobalt and Nickel Arsenides.—Qualitative chemical tests on the hard white mineral surrounding native silver and associated with many of the other metallic constituents show the presence of cobalt, nickel and arsenic. The orthorhombic form, anisotropism in a polished surface, hardness, and reaction to common etch reagents as given by Thomson,[8] clearly indicate that this material belongs to the group of cobalt and nickel arsenide minerals. Both safflorite, the cobalt arsenide, and rammelsbergite, the nickel arsenide, are believed to be present, although the two minerals cannot always be distinguished from each other in a polished surface. Wherever these minerals are discussed in connection with this study, they are simply referred to as arsenides of cobalt or nickel without attempting to indicate whether safflorite, rammelsbergite, or both minerals are present in every instance. Their significance as regards the origin of the silver minerals is the same in each case. So far as known, this is the first reported occurrence of these minerals in Mexico.

The occurrence of these arsenides is strikingly similar to their occurrence at Cobalt and South Lorraine in Ontario. They generally border grains of native silver or other metallic constituents. Gangue minerals are surrounded in a similar manner, as though the arsenides had sought out the contacts between individual grains for their formation. They also occur as clusters of individual crystals in gangue or associated with metallic minerals. In such cases beautiful stellar-shaped twins and rhombic forms are common. These stellar-shaped twins are identical to published photographs of twinned safflorite from Cobalt, Ontario, by Schneiderhöhn and Ramdohr.[9]

The deposition of cobalt and nickel arsenides is believed to have accompanied the final stages of hypogene silver mineralization. They are clearly of primary origin, and bordering native

[8] Thomson, Ellis: A Qualitative and Quantitative Determination of the Ores of Cobalt, Ont. ECON. GEOL., vol. 25, page 471, 1930.

[9] Schneiderhöhn, H., and Ramdohr, P.: Lehrbuch der Erzmikroskopie, Bd. II, p. 212, 1931.

silver as they do, they offer the strongest evidence for the primary origin of the native silver as well.

Gold.—Native gold is found near the eastern end of the vein below the 300 foot level and is sometimes present in sufficient quantity to be visible to the unaided eye. Ore from this location has increased the gold assay of shipments to as high as 0.5 ounce per ton.

Vein material with which the gold is associated consists almost entirely of sugary-textured, crystalline quartz which has replaced large masses of barite. Although numerous vugs exist in this part of the vein, the colloform banding typical of quartz elsewhere is absent. The gold occurs completely inclosed in quartz and is sometimes associated with argentite. It is believed to be primary in origin and to have accompanied the final introduction of quartz.

Paragenesis of the Hypogene Minerals.—It has not been possible to establish a definite sequence in order of deposition for all the hypogene minerals. This is due to overlapping of mineralization in some cases, with consequent conflicting evidence in polished surfaces, and to the isolated occurrence of others. Where the relations are quite clearly shown, however, it has been possible to work out the following sequence: pyrite, pyrargyrite and polybasite, galena, sphalerite, argentite, native silver, nickel and cobalt arsenides. Chalcopyrite and tetrahedrite were observed only in subordinate amounts and gave no definite clue as to their paragenesis. Gold was not seen in direct contact with other ore minerals. However, its association with argentite in good crystalline quartz in the lower portion of the mine suggests that it is related to the final stages of metallic mineralization. A chart indicating the paragenesis of the minerals is shown in Fig. 11.

SUPERGENE MINERALIZATION.

Vugs, drusy cavities and other openings are sufficiently abundant in the vein to enable meteoric waters to reach relatively deep portions of the mine, so that some supergene mineralization should occur throughout most of the present workings. Essentially all the mineralization that can readily be recognized as due to such processes is confined to the more porous and vuggy

areas or to openings that exist along the walls of the vein. In these areas oxidation products are found in considerable abundance.

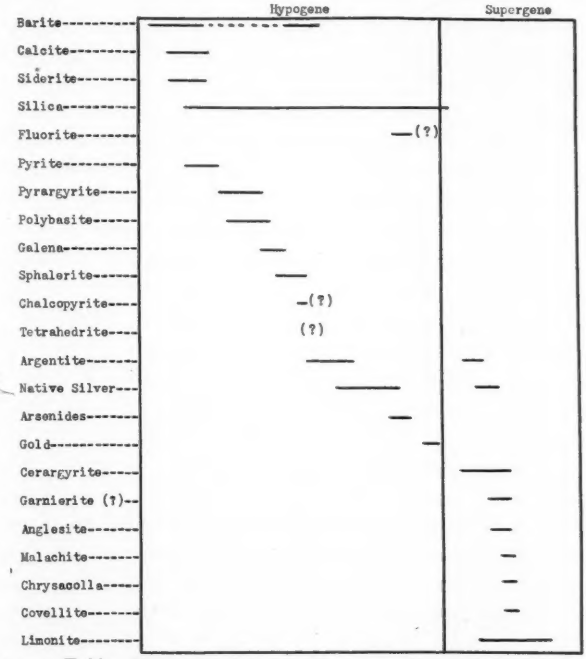


FIG. 11. Table showing the paragenesis of minerals in the Florencia-Magda vein.

Cerargyrite.—This chloride of silver was an important constituent of the ores in the upper portion of the mine, where it occurred as incrustations on vein matter and in vugs or other openings. Although not so abundant in the lower levels, it persists to the present depth of the mine and is commonly found as small, well developed cubes attached to the walls of cavities or vugs. Such occurrences are generally completely isolated from other silver minerals from which the cerargyrite may have been derived, and it is reasonable to suppose that the silver had been transported by meteoric solutions from mineralized areas above.

Native Silver.—As previously stated, supergene silver is also believed to be present in the veins. In those areas where oxidation is pronounced, fine wires and plates of native silver are sometimes found. In such instances, however, galena, sphalerite and the arsenides of cobalt or nickel are absent. One specimen was also noted that showed native silver and cerargyrite that had formed at the expense of argentite.

Argentite.—Although argentite formed by supergene processes is undoubtedly present in the mine, it is not always possible to distinguish it from hypogene argentite. In those areas where oxidation has been prominent, however, grains of the silver sulphide commonly occur disseminated through the altered vein material, and in these areas the argentite is probably of supergene origin.

Garnierite (?).—A green mineral occurring as an incrustation on fluorite crystals gave microchemical tests for nickel and zinc. This mineral has the general appearance of garnierite, although sufficient amounts of the material could not be obtained to make conclusive tests. It is also possible that this may be de-saulesite, a zinkiferous variety of garnierite described by Koenig [10] in 1885 from Franklin Furnace, New Jersey. Analysis of the Franklin Furnace material showed the presence of 4 per cent zinc.

Anglesite.—Oxidation of galena has resulted in the formation of anglesite in some instances. It usually exists only as a thin border around galena and is not widespread in its occurrence.

Malachite and Chrysocolla.—These two minerals are only sparsely distributed through the vein and usually occur as a coating on gangue minerals or in vugs.

Covellite.—Covellite was observed as small particles in a polished surface of altered vein material. Remnants of the primary minerals from which it had been derived tested for tetrahedrite.

ORIGIN OF THE ORES.

The general character and association of metallic minerals at Sabinal afford the most reliable criteria for the origin of the

[10] Koenig, George A.: Proc. Phila. Acad. Nat. Sci (3), vol. 19, p. 185, 1889.

silver minerals. Most of the minerals described are generally considered as typically primary in origin. Associated as they are, with the silver minerals intimately intergrown with pyrite, sphalerite and galena, and surrounded by cobalt and nickel arsenides, the conclusion is that the silver minerals are also of primary origin. This association would be extremely unlikely to occur as the result of supergene solutions, and no deposit is known to the writer where such an assemblage of minerals is generally believed to be of supergene origin.

The near-by presence of a large intrusive mass, the metallic deposits in the contact zones and the alteration of the wall rock of the veins by solutions similar in composition to the igneous mass, all point to the alaskite intrusive as the most obvious source of the mineralizing solutions.

Mineralization in the Florencia-Magda vein is believed to be of low-temperature, epithermal character. This contrasts strongly with the obviously high-temperature contact deposits near-by and suggests that the solutions responsible for mineralization in the fissure veins were given off after the igneous mass had cooled to some extent, and that they were the last residual products of this cooling mass.

Association of native silver with the arsenides of cobalt and nickel resembles the occurrence of these minerals at such places as Cobalt, Ontario, at Schneeberg, Saxony, and near Wickenburg, Arizona. The country rock, however, and the character of the veins at each of these localities are quite different. At Sabinal the veins are distinctly of the low-temperature, epithermal type, characterized by an abundance of open vugs and intricate colloform banding of the silica, whereas the veins at Cobalt and at Schneeberg are classified by Lindgren [11] as mesothermal in character and appear to have been formed at somewhat higher temperature.

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[11] Lindgren, Waldemar: Mineral Deposits, 4th ed., 1933.

STRUCTURAL RELATIONS OF SOUTHERN APPALACHIAN ZINC DEPOSITS.

L. W. CURRIER.[1]

INTRODUCTION.

THE zinc deposits of the southern Appalachian region lie chiefly between Roanoke, Va., and Knoxville, Tenn. They occur in breccias of Cambrian and Ordovician dolomites and limestones. There are about 85 mines and prospects, but only three have been extensively developed and are now operating—those of the Bertha Mineral Company (subsidiary of New Jersey Zinc Co.), at Austinville, Va.; the Universal Exploration Company, at Jefferson City, Tenn.; and the American Zinc Company of Tennessee, at Mascot, Tenn. In recent years extensive prospecting has been undertaken in the Jefferson City district. Considerable mining of oxidized ore bodies has been carried on in the Embreeville district, and lead and zinc sulphides occur in the country rock (Shady dolomite);[2] and some production of galena is reported.[3]

Nason,[4] in two papers published in 1917, has suggested a deep origin for these deposits from ascending solutions and, without definitely stating that they are of igneous origin, he rejects the idea of a meteoric origin for them. In an earlier paper,[5] however, he suggested the possibility of an igneous origin for Appalachian zinc deposits in general.

[1] Published by permission of the Director of the United States Geological Survey.

[2] Secrist, M. H.: Zinc Deposits of East Tennessee. Tenn. Dept. Education, Div. Geology, Bull. 31, p. 145, 1924.

[3] U. S. Bur. Mines, Mineral Resources, 1931.

[4] Nason, F. L.: Characteristics of the Zinc Deposits in North America. Amer. Inst. Min. and Met. Eng. Trans., vol. 57, pp. 830–855, 1917; Principles Governing Zinc Ore Deposits. Min. and Sci. Press, vol. 115, pp. 647–651, 1917.

[5] Nason, F. L.: Zinc Deposits of Eastern Tennessee. Eng. and Min. Jour., vol. 99, p. 734; April 24, 1915.

Ball and Thompson [6] believed definitely in a magmatic origin and emphasized the association of the ore bodies with "unusually disturbed strata," in some places with strike faults, and at no particular stratigraphic horizon. Watson,[7] on the other hand, although recognizing the common relation of the ores to regional structure, believed that they were formed by circulating meteoric waters that collected the metals from the inclosing limestones and dolomites in which they were originally deposited, after being released by denudation of pre-Cambrian source rocks. He emphasized also the restriction of the ore minerals to definite stratigraphic horizons. Indeed, the belief in such restriction is apparently common, and it is not surprising that, in general, the deposits have been looked upon as of supergene origin, in a broad way of the type of the Missouri deposits, and as having formed in breccias of cave-collapse rather than of tectonic origin. Ulrich [8] has stated his belief in the cave-collapse origin of the breccias and argues that the close stratigraphic limitation of the ores in the Mascot-Jefferson City region precludes the possibility that they occur in fault breccias. This aspect of the problem is discussed on a later page.

The purposes of the present paper are to give a picture of the broad geologic setting of the deposits, and to present reasons for the writer's belief that solutions ascending from comparatively great depths along fissure and fracture zones deposited the ore minerals in breccia zones of tectonic origin. The conclusions, so far as the Virginia deposits are concerned, are drawn almost entirely from a detailed study of areal features, inasmuch as access to the mine at Austinville, except to the inactive top (adit) level, was not permitted. In Tennessee several days were spent underground at each of the mines at Mascot and Jefferson City. A number of outlying prospects in both Virginia and Tennessee were also visited. This paper is the outgrowth of detailed study

[6] Ball, S. H., and Thompson, L. S.: Southwest Virginia Lead-Zinc Deposits. Eng. and Min. Jour., vol. 102, pp. 735–737, 1916.

[7] Watson, T. L.: Lead and Zinc Deposits of Virginia. Va. Geol. Surv. Bull. 1, pp. 128–129, 1905.

[8] Ulrich, E. O.: Origin and Stratigraphic Horizon of the Zinc Ores of the Mascot District of East Tennessee. Jour. Wash. Acad. Sci., vol. 21, no. 2, pp. 30–31, 1931.

and mapping of the southwestern Virginia zinc belt, conducted by the Virginia Geological Survey in co-operation with the U. S. Geological Survey.

The writer feels particularly indebted to D. F. Hewett, of the U. S. Geological Survey, under whose general direction the Virginia work was started and who for several years has been greatly interested in problems relating to the southern Appalachian deposits. He has given the writer free use of his notes and has helped greatly with advice and discussion, both in the field and in the office. Charles Butts spent several days in the southwestern Virginia district, and Josiah Bridge made his geologic map of the Mascot-Jefferson City area available for study. G. F. Loughlin spent several days in Virginia and Tennessee with the writer, and made valuable suggestions in matters of treatment and interpretation. To officials of the American Zinc Company of Tennessee and the Universal Exploration Company, the writer is indebted for permission to study the mines at Mascot and Jefferson City. Mark H. Newman, geologist at Mascot, and John A. Crawford, geologist at Jefferson City, gave generously of their time and pointed out many features of particular value. Arthur Bevan, State Geologist of Virginia, who gave impetus to the study of Appalachian zinc deposits by his initiation of a mapping project in the southwestern Virginia field as a co-operative enterprise with the U. S. Geological Survey, has given permission for the use of certain pertinent facts concerning that area.

ZINC DISTRICTS OF THE VALLEY.

Southwestern Virginia.—Although a large number of prospects and mineral showings are known along the 100-mile stretch of the Virginia Valley from Roanoke to Marion, at only four places have sulphide ores of zinc and lead been mined commercially—in the Austinville, Ivanhoe, Cedar Springs, and Rye Valley districts. Present mining is confined entirely to Austinville and Ivanhoe. These four districts lie within a 30-mile strip of the Valley extending from Austinville, on the New River, to Sugar Grove (Fig. 1). A number of prospects occur several miles both

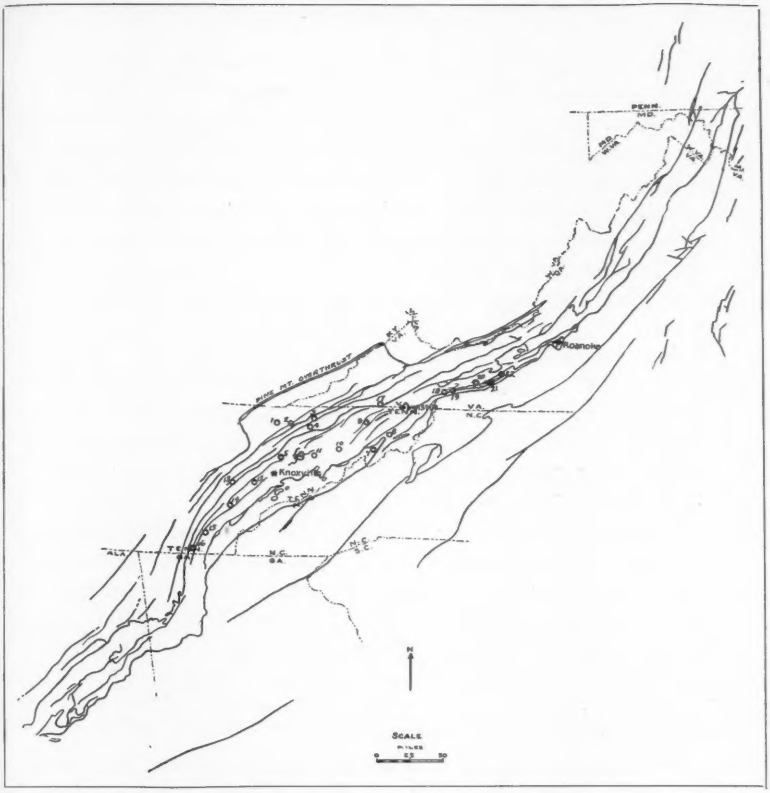

FIG. 1. Map showing distribution of zinc mines and prospects in relation to major faults of the southern Appalachians. (Fault data from Geologic Map of the United States, U. S. Geol. Survey, 1932, with slight modification and additions from several sources.) Circles represent approximate centers of zinc districts.

Tennessee: (1) New Prospect district; (2) Straight Creek district; (3) Evanston district; (4) Copper Ridge district; (5) Mascot district; (6) Jefferson City district; (7) Embreeville district; (8) Watauga Point prospect; (9) Fall Branch district; (10) Naff prospect; (11) Felknor prospect; (12) Friendsville prospect; (13) Patrick prospect; (14) Eve Mills prospect; (15) Hambright mine (abandoned); (16) Hardwick mine (abandoned).

Virginia: (17) Arcadia district; (18) Adwolf district; (19) Sugar Grove (Rye Valley) district; (20) Cedar Springs district; (21) Austinville-Ivanhoe district; (22) Bertha district.

east and west of this area, most of which are included in the map of the southwestern Virginia zinc belt as mapped for the Virginia Geological Survey.[9] The mine of the New Jersey Zinc Company, at Austinville, is one of the two largest producers of southern Appalachian zinc ores. At Ivanhoe small amounts have been mined rather regularly for several years. The workings at Cedar Springs (zinc only), and Sugar Grove (Rye Valley; lead) have not been operated since 1910.

Eastern Tennessee.—The 57 mines and prospects recorded by Secrist [10] are classified by him into 15 districts, situated in several limestone belts of the broad Valley province. The westernmost lies along the Powell River (New Prospect district) not far from the edge of the Cumberland Plateau; the easternmost (Watauga district) is just west of Elizabethton, at the eastern border of the Valley, where the Cambrian limestones of the Valley are overlain by thrust blocks of the older Cambrian quartzites. One district (Embreeville) is in a small synclinal valley underlain by Shady dolomite (Lower Cambrian) that is a part of an overthrust block. The several districts of Tennessee are indicated in Fig. 1 by numbers. The only districts of productive importance so far are Mascot, Jefferson City, and Embreeville. The Embreeville district produces only oxidized ores.

GENERAL GEOLOGIC RELATIONS OF THE ZINC DISTRICTS.

Stratigraphic Position of Zinc Deposits.—The southern Appalachian Valley is underlain by thick dolomite and limestone formations of Cambrian and Ordovician age, alternating in places with beds of shale and, subordinately, of sandstone. Essentially it is a limestone-dolomite valley in all places where zinc deposits are known, and only in such rocks have zinc bodies been found. The theory that the ores were deposited in breccias of cave-collapse origin is founded largely on the belief that they occupy definite and narrowly limited stratigraphic positions. Close ex-

[9] The author's detailed map of the zinc belt is to be published later by the Virginia Geological Survey.

[10] Secrist, N. H.: Zinc Deposits of East Tennessee. Tenn. Dept. Education, Div. Geology, Bull. 31, 1924.

amination of the data now available, however, shows that this is not the case. Within any one district, indeed, the ore bodies are generally confined to a single formation, but not to a closely limited position within the formation, except possibly in the Mascot-Jefferson City belt, where the exploited bodies seem to occur only in the lower part of the upper third of the Knox dolomite. The productive zone in this belt is probably about 150 to 200 feet thick.

The generalized stratigraphic column for the southern Appalachian Valley province is as follows:

	Eastern Tennessee	Intermediate	Southwestern Virginia
Ordovician	Holston limestone Lenoir limestone Mosheim limestone		
	Knox dolomite		
Cambrian	Nolichucky shale [a]	Nolichucky shale	
	Maryville limestone [a] Rogersville shale [a] Rutledge limestone [a]	Honaker limestone	Elbrook dolomite
	Rome formation	Rome formation	Rome formation
	Shady dolomite		Shady dolomite Erwin quartzite Hampton shale Unicoi formation
			Pre-Cambrian

[a] In belts west and north of the Mascot-Jefferson City belt these formations are not differentiable, and their stratigraphic position is occupied by the Conasauga shale.

In Tennessee, one district (Evanston) carries ores in a dolomite bed within the Rome formation, and another (Embreeville) carries ores in the Shady dolomite. In all other districts the ores are in the Knox dolomite. In the Copper Ridge district, according to Secrist, the ores occur at several horizons, estimated to range from 420 to 1,015 feet stratigraphically below the top of the Knox.

In southwestern Virginia all the productive deposits are within the Shady dolomite, and mineral bodies are known through a range of 1,500 to 1,800 feet in the Ivanhoe-Austinville district, though at present mining is limited to approximately the upper half of the formation.

Structural Positions of Zinc Deposits.—The zinc deposits lie within strongly folded and thrust-faulted areas of the Appalachian Valley. Fig. 1 shows the distribution of the districts with reference to major overthrusts. The scale of the map does not permit the showing of all the known details of faulting, but the map gives a general idea of the relative degrees of faulting in different parts of the Appalachian province. As the faults are strike faults, the traces indicate also the general trend of the regional axial lines.

The zinc deposits of both Virginia and Tennessee are localized in areas that display the effects of pronounced thrust faulting and related cross faulting. Published geologic maps show no faults in the New Prospect and Straight Creek districts (Fig. 1), but recent observations by Josiah Bridge and the writer clearly indicate a structural complexity due to faulting at both places. The general character of the deformation at New Prospect has been described by both Secrist[11] and Miser.[12] At the Straight Creek mine, recently studied by Mr. Bridge and the writer, several prominent strike thrust faults and sharply diagonal thrust (or tear?) faults are clearly evident. At both New Prospect and Straight Creek the mineral bodies are in breccia zones adjacent to faults.[13] It should be pointed out that these two districts, situated on the Powell and Clinch rivers respectively, are within the area of a broad, low anticline that appears to comprise the overriding block of the Pine Mountain overthrust. This fault is believed to underlie the region at a comparatively shallow depth and

[11] Secrist, M. H., *op. cit.*

[12] Purdue, A. H.: The Zinc Deposits of Northeastern Tennessee. Tenn. Geol. Survey Bull. 14, 1912 (descriptions of prospects by Purdue and H. D. Miser).

[13] Since the preparation of this paper, the writer has begun a detailed study of these areas under the auspices of the Public Works Administration, acting through the United States Geological Survey with the co-operation of W. F. Pond, State Geologist of Tennessee.

at a nearly horizontal attitude. Cross faults are clearly apparent in the Virginia field and in some of the Tennessee districts. In some of the minor districts such faults, if present, have not yet been discovered, owing to poor surface exposures or inadequacy of subsurface developments, or possibly because tectonic adjustments of this type may have been distributed as very small displacements along a large number of cross fractures, as appears to be the case at Mascot, Tenn.

Most of the known zinc deposits are in beds of southeast dip that constitute the limbs of anticlines. Commonly throughout the Valley province, erosion removed the crests of most of the anticlines, so that homoclinal southeastward-dipping beds are exposed. Of 53 mines and prospects in Tennessee, 42 occupy such positions, and only 4 are in approximately horizontal beds. In Virginia large-scale mining has been carried on only at Austinville, where the deposits are exploited in the southeast limb of a prominent anticline; some small mines and prospects in adjacent territory (Ivanhoe) are found also in northwestward-dipping beds of the same fold and in proximity to a zone of pronounced cross faulting. At Cedar Springs and Rye Valley the deposits are in steeply dipping beds of closely compressed and slightly overturned local folds, which were developed, however, in the southeast limb of a large regional anticline.

In general, characteristic structural features of the zinc areas are (1) thrust faults; (2) cross faults, probably true tear faults in part; (3) "slicing," or sheet jointing normal to the strike of the beds; (4) sharp flexures in anticlinal axes; (5) sharp anticlinal folds; and (6) breccias of tectonic origin. Compressive forces that generally resulted in obvious thrust faulting appear to have caused the formation of the breccias in which zinc and lead minerals were deposited. Many cross faults and sheeted zones are heavily mineralized. In Virginia, areas showing pronounced deflections in the trend of the anticlinal axis also show the phenomena of slicing and cross faulting, and doubtless all these features are strain effects of a single cause—that is, undistributed thrust forces, acting late in the thrust epoch.

Zinc Area of Southwestern Virginia.

The area extending from the Bertha district on the east to the Adwolf district (Fig. 1) was mapped in detail for the co-operative project of the State and U. S. Government Surveys. Only

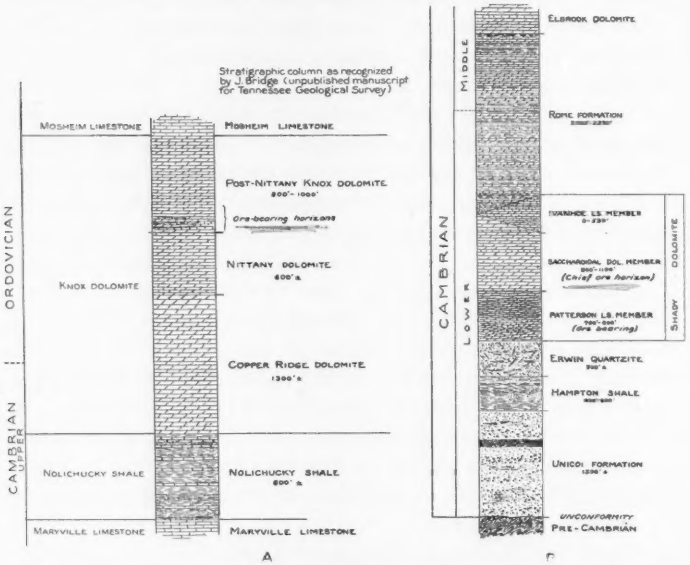

FIG. 2. Generalized columnar sections of producing zinc districts, showing ore horizons and lithologic character of formations above and below. *A*. Mascot-Jefferson City, Tennessee (according to J. Bridge—personal communication). *B*. Austinville-Ivanhoe, Virginia.

The writer's subdivisions of the Shady dolomite in southwest Virginia are: Patterson limestone—banded ("ribbon") dark limestone and dolomite, 700 to 800 feet thick, transitional at base with Erwin quartzite, and at top with saccharoidal dolomite; the saccharoidal dolomite member, 800–1100 feet thick, containing characteristic light-colored dolomite beds with saccharoidal texture (section exposed in railroad cut one mile east of Ivanhoe); Ivanhoe limestone (0 to 550 feet thick)—massive, dense, gray limestone with a few thin beds of crystalline dolomite (exposed in and above quarry along railroad one mile east of Ivanhoe). Rome beds overlie the Ivanhoe limestone conformably at Ivanhoe. The Ivanhoe limestone is of local development.

general features of structure and stratigraphy as related to zinc deposits will be mentioned here.

The stratigraphic column for the southwestern Virginia zinc area is given in Fig. 2–B. The known zinc deposits, with the possible exception of one exposure, are all within the Shady dolomite (Fig. 2). This formation is composed chiefly of dolomite, and ores have been taken almost exclusively from the middle or saccharoidal dolomite member, although in the Austinville-Ivanhoe district the dolomitic parts of the Patterson limestone member show considerable mineralization. Limestone beds in the formation are not mineralized. The Shady dolomite is overlain by a thick shale formation and underlain by massive quartzite. This sequence is probably significant as regards the limitation of zinc ores to the Shady dolomite.

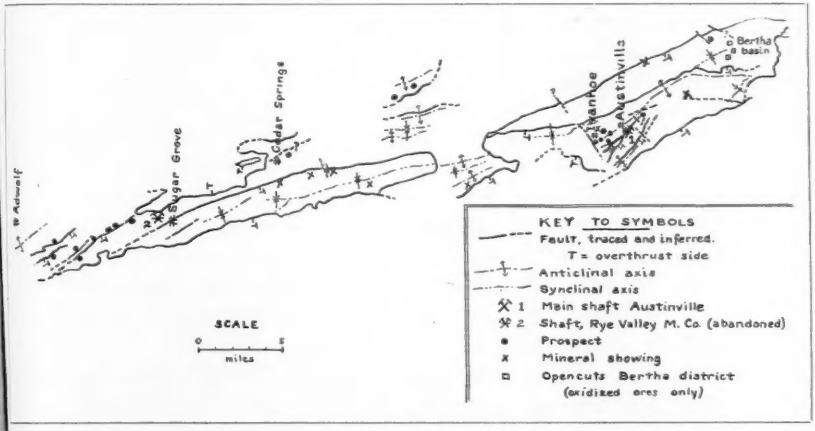

FIG. 3. Map of southwest Virginia zinc belt, showing major structural features and locations of mines and prospects. Condensed and generalized from original map prepared for Virginia Geological Survey. (Published by permission of the State Geologist of Virginia.)

Figure 3 indicates the larger structural features of the mapped area and the geographic distribution of mines and prospects with reference to thrust faults, cross faults, and axes of folds. Deformation by folding, twisting, and faulting, as shown by surface

conditions, has been decidedly more intense in the Austinville-Ivanhoe district than elsewhere in the area. Here the large overthrust block that includes the Austinville anticline is exceptionally deformed by subordinate steeper thrusts, cross shears, and related strains, indicating a stage of undistributed stresses that developed relatively late in the thrust epoch. Some of the cross faults may indeed be true tear faults. Cross sheeting and local deflections of the anticlinal axis are particularly marked.

The relation of mineral bodies to cross faults within the mine at Austinville cannot be stated from personal observation. On the surface, however, at several places in the Austinville Ivanhoe district, the zones of cross sheeting are mineralized. At Ivanhoe a prominent cross-fault zone carries ore bodies, and on this zone there has been some shaft mining. The writer had access only to the top or adit level of the mine at Austinville, so that it was impossible to trace structural features and ore bodies into the lower workings. The distribution of stopes in the adit level, however, indicates (1) ore shoots separated by relatively barren ground along the drift, which follows the strike of the beds, so that mineralized zones are definitely oriented across the strike, and (2) ore shoots at several horizons in the country rock.

The ores of the district are found consistently in dolomite breccias whose textural characteristics and association with faulted and folded beds indicate their tectonic origin. Coarsely crystalline white vein or "gangue" dolomite is the common cementing material of the breccias and together with rock fragments has been partly replaced by the sulphide minerals.

The mineralogy of the ores is simple. At Austinville the association is sphalerite, galena, pyrite, dolomite, cherty silica, fluorite, and barite. At the abandoned mine of the Rye Valley Mining Company, in the Sugar Grove district, galena was the chief sulphide. Elsewhere the zinc deposits carry practically no lead mineral. Besides occurring at Austinville, fluorite is present also at Sugar Grove, Cedar Springs, the Riggles prospect (2.5 miles east of Crocket), and Allisonia. Like fluorite, barite is nowhere prominent, but is found in the Ivanhoe-Austinville dis-

trict. Considered in a broad way, sphalerite and pyrite are widely distributed in the southwest Virginia area, whereas galena and fluorite are concentrated at two or three localities. No other suggestion of zonal distribution can be made from the writer's data.[14]

Jefferson City District, Tennessee.

Since 1928 the Universal Exploration Company has been developing and mining bodies of sulphide ore at the Davis mine, at the southern edge of Jefferson City, Tenn. This is the only mine in operation in the district at the present time. The Jarnigan mine of the American Zinc Company, a short distance northeast of the city, is temporarily inactive. The shaft of the Grasselli Chemical Company, at the "carbonate" pits, about 3 miles southwest of the city, was sunk for the purpose of developing sulphide ore bodies but apparently has yielded no production. Besides these mines, there are several prospects in the district.

The ore bodies at Jefferson City occur in approximately the lower part of Bridge's post-Nittany division of the Knox dolomite, as shown in Fig. 2–A.

The mineralized beds are reported to be limited to a stratigraphic interval of about 200 feet. In this zone dense limestones are interbedded with the dolomites, and the richer ores have largely replaced the fractured limestone. Ore bodies continue, however, through a considerable thickness of the more highly brecciated overlying dolomite.

Structurally the most impressive areal feature shown on Bridge's map of the district[15] is a major overthrust fault, the sinuous trace of which passes a short distance south of the Davis mine. The beds in the footwall block are folded into a broad anticline of low southwest pitch, and the several mines and pros-

[14] Since the presentation of this paper at Princeton in July, 1933, W. H. Brown, geologist at the Austinville mine, has presented a paper (XVI International Geological Congress, Washington, July, 1933) in which he points out, for that mine, (1) that cross faults were the mineralizing fissures and (2) that there is a definite zonal arrangement of galena and sphalerite in the deposits with respect to these fissures and the adjacent ore breccias.

[15] Manuscript prepared for Tennessee Geological Survey.

pects are on the southeast limb, in which the dips are generally 5° to 15°, rarely as much as 20°. Apparently the overthrust is one of very low angle, nearly parallel to the bedding—a condition that is considered favorable to the formation of tectonic "bedding" breccias, as discussed in a later paragraph. The details of the ore occurrence and the relation of mineralized portions to structural features at the Davis mine are confidential matters, but it can be stated that structural control of the mineralization is clear.

The primary ores are of two types—the dolomite breccia type, similar in general to the Virginia ores, and the "recrystallized" limestone type, consisting of slightly brecciated and largely replaced limestone. The "recrystallization" was brought about by the dolomitization of the dense limestone during the period of mineralization. Coarse white "gangue" dolomite as veinlets and as matrix of the breccia ore is also a marked feature, though to a less degree than at Mascot.

Mascot District.

The only mine operating in the Mascot district is that of the American Zinc Company of Tennessee, about 13 miles northeast of Knoxville. Here the first shaft for the mining of sulphide ore was sunk in 1900. The present workings are extensive and reach the 13th level at a vertical depth of 800 feet. According to Newman [16] prospecting has proved ore to a vertical depth of 1,000 feet, and "at these depths no more pronounced variations in metal content, degree of shattering, or mineral association have been noted than are common at less depths."

At Mascot, as at Jefferson City, the ores seem to be limited to a stratigraphic range of about 200 feet. The exact correlation between the ore horizons of the two areas has not, however, been satisfactorily demonstrated, although it is clear that at both Mascot and Jefferson City the ores occur in the lower part of Bridge's post-Nittany division of the Knox dolomite. Southwest of Mascot, through a distance of 8 to 10 miles, there are several

[16] Newman, M. H.: The Mascot-Jefferson City Zinc District of Tennessee. XVI Int. Geol. Cong. Guidebook 2, p. 158, 1932.

prospects that contain sphalerite, chiefly at the same horizon, but in one or two places in the Nittany dolomite of Bridge's classification. It is evident, therefore, that although the chief ore bodies so far discovered in the Mascot district are at a fairly definite horizon, the regional mineralization was not strictly confined to this horizon.

The mine at Mascot is on the southeast limb of a broad open fold in Cambrian and Ordovician rocks. The dips of the strata are somewhat greater than at Jefferson City but average only about 20°. No major regional overthrust passes through the mineralized area, although Keith's map [17] shows an extensive overthrust of northeast-southwest trend about 3 miles south of Mascot, and another about 2 miles north. Bridge shows on his map a fault of uncertain length and continuity about a mile northeast of the mine, where the Mosheim limestone provides a satisfactory marker. Thus it is seen that the Mascot district is in a belt deformed by regional overthrusting as well as by simple folding. East of Mascot, also, Bridge's studies have demonstrated localized warping in addition to the major folds of Appalachian type.

No cross faults of large displacement are evident within the mine at Mascot, but there are many pre-mineral displacements that, considered all together, reflect considerable aggregate adjustment to undistributed stresses and have aided in the extensive brecciation of the country rock. In addition, relatively thin zones of "rubble" breccia strongly suggest thrusting that was localized chiefly along bedding planes.

In a number of places a traverse from hanging wall into footwall of the ore bodies showed first a general cracking of the beds without displacement of the blocks in the hanging wall; as the ore zone is approached and entered the cracking is more intense ("shatter" or "crackle" breccia); locally within the ore body, especially near the footwall, thinner "rubble" zones of highly brecciated material are found; in the footwall the breccia is again of the "shatter" or "crackle" type, but the change is more abrupt than that in the similar zone near the hanging wall. This

[17] Keith, Arthur: U. S. Geol. Survey, Geol. Atlas, Maynardville folio (no. 75), 1901.

type of breccia dies out rather gradually, through a zone 30 or 40 feet thick in places, into beds that show simple jointing effects. Figures 5 to 8 display types of shatter brecciation in the walls of ore zones.

The ore bodies at Mascot are especially large; they average 50 to 60 feet thick and are in a few places much thicker, and as much as 150 feet wide.

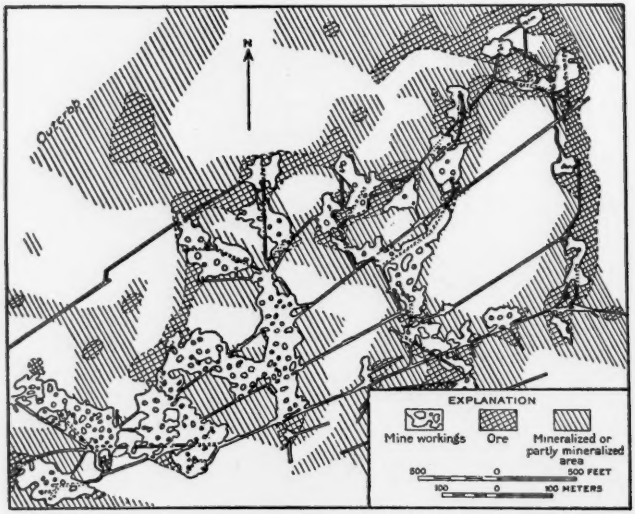

FIG. 4. Map of part of workings of mine No. 2, Mascot, Tenn., showing trends of major ore bodies and their relation to each other and to areas of lower-grade mineralization. (After M. H. Newman, in Guidebook 2, Int. Geol. Congress, Washington, D. C., 1932.)

Suggestive orientations of major ore bodies are indicated in Fig. 4. Although the ore boundaries, except the floor, are chiefly economic rather than structural limits, the mine map suggests a general elongation and orientation of the mineable portions transverse to the strike of the beds. The main stope workings clearly follow two definite directions—N. 60°–70° W. and N. 5° W. to N. 5° E., with local divergences in other directions. These main directions coincide with two systems of minor faults that

were observed on the main level, where readings of N. 60° W. and N. 5° E. were obtained. These conditions are to be regarded as suggestive for further investigation rather than conclusive evidence, for there remains to be made a comprehensive study of local fractures in relation to zinc content throughout the mine.

In general the footwalls of the ore bodies are altered thin brown limestone beds within the dolomite formation, which have suffered brecciation and dolomitization similar to that at Jefferson

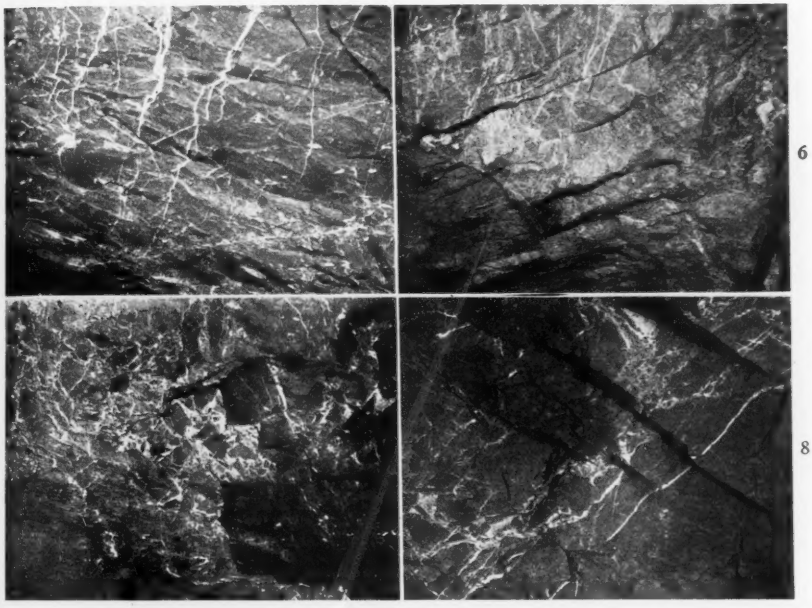

FIG. 5. Fractures in hanging-wall of ore zone, Mascot. Typical of hanging-wall relatively remote from ore zones. (Photo by D. F. Hewett.)

FIG. 6. Fractures in roof of ore zone, 9–13 level incline, Mascot. (Photo by D. F. Hewett.)

FIG. 7. Highly brecciated zone, crosscut main level, Mascot. (Photo by D. F. Hewett.)

FIG. 8. Fractures in footwall dolomite, 11 level crosscut, Mascot. (Photo by D. F. Hewett.)

City. The richest portions of the ore bodies are in the lower third, just above and including dolomitized portions of the limestones, and their positions are also the sites of greatest shattering in the dolomite country rock. Newman [18] states:

> The ore deposits are not co-extensive with the ore-bearing strata but are generally large both in cross-section and in length. Their outlines are irregular, and ore shoots follow winding and sinuous courses. The extensive developments at Mascot show that many of the ore bodies are connected and tend to form a network enclosing unmineralized areas.

The composition and structure of the ore at Mascot are very simple. Sphalerite and subordinate pyrite are the chief sulphide minerals; galena is extremely rare. The gangue is composed of coarse white dolomite as veinlets and breccia matrix, partly replaced dolomite country rock, and dolomitized limestone. Both rock fragments and matrix are crossed by dolomite-sphalerite veinlets. Several thin sections have shown replacement of the white vein dolomite by sphalerite. Chert of the mineralizing epoch is present. It is noteworthy that here, as at Jefferson City, vugs are rarely found and larger cavities are practically absent except close to the surface, where they were formed by subsequent solution through the agency of surface waters.

Other Districts in Tennessee.

The data for the following brief review of other zinc districts in Tennessee have been obtained partly from a study of the literature.[19] The writer has visited several of the districts, including the New Prospect, Straight Creek, Embreeville, and Felknor mines.

New Prospect District.—This district includes the New Prospect mine and several prospects situated along a stretch of about 12 miles in the Powell River Valley (Fig. 1). The geologic map

[18] Newman, M. H.: *Op. cit.*, pp. 155–156.

[19] Secrist, M. H.: Zinc Deposits of Tennessee. Tenn. Dept. Education, Div. Geology, Bull. 31, 1924. Purdue, A. H.: The Zinc Deposits of Northeastern Tennessee (descriptions by Purdue and H. D. Miser). Tenn. Geol. Survey Bull. 14, 1912. Nason, F. L.: Zinc Deposits of Eastern Tennessee. Eng. and Min. Jour., vol. 99, p. 734, April 24, 1915.

of this region, by Keith,[20] shows the New Prospect mine and near-by prospects to be in the lower part of the Knox dolomite, nearly on the crest of a broad anticline, about 10 miles across, and in the extensive overthrust block of the Pine Mountain overthrust. The structural relations of this part of Tennessee[21] suggest that the fault surface is nearly horizontal beneath Powell Valley. The maps show no major fault traces within several miles of the district. On the other hand, the lithologic character of the Knox formation, the lack of known narrowly limited key horizons within it, and the fact that exposures are rare over large areas, because of the thick mantle of red clay, render it likely that faults of small displacement are not determinable.

The structural setting of the workings at New Prospect mine is, however, clearly recognizable, and has been described by Purdue,[22] Secrist,[23] and Nason.[24] According to Secrist, "mineralization and fracturing are closely related and combine to form an ore body of rather definite outline." It is clear that the ore minerals (sphalerite and galena) were deposited in a shattered zone, 50 to 70 feet wide, between two nearly vertical zones of closely spaced faults of east-west strike. Nearly horizontal grooves on these faults indicate a tear-fault type of adjustment at a sharp angle across the regional strike. Horizontal adjustment also occurred along certain bedding planes. According to Nason, additional local faulting is indicated at some distance both west and east of the mine workings by displacement of the "ribbon limestone" that forms the floor of the ore body at the mine; he states further that similar fissures have been proved to extend, with mineralization, to a depth of 1,200 feet below the local base-level, and according to his views this circumstance precludes a supergene origin for the mineralizing solutions.

The ore bodies at the New Prospect mine occur in the lower part of the Knox dolomite (Copper Ridge dolomite of Bridge's

[20] Keith, Arthur: *Op. cit.*

[21] *Idem:* also Briceville folio (No. 33), 1896.

[22] Purdue, A. H.: *Op. cit.*, p. 45.

[23] Secrist, M. H.: *Op. cit.*, pp. 38–41.

[24] Nason, F. L.: Geological Anatomy of a Tennessee Zinc Mine. Eng. and Min. Jour., vol. 100, p. 259, Aug. 14, 1915.

classification) and hence are much lower stratigraphically than those in the Mascot and Jefferson City districts.

Straight Creek District.—This district comprises the Straight Creek mine and several prospects that occur in the lower part of the Knox dolomite, 10 to 12 miles east of the New Prospect mine (Fig. 1). A major overthrust passes through this belt.[25] The ore body at the Straight Creek mine was developed through a vertical distance of 150 feet in and along the hanging wall of a fault that dips 70° S. and intersects the south limb of a distinct anticline near its crest. According to observations made in 1931 by D. F. Hewett, the strike of the fault at the face of the adit is N. 75° E., and that of the bedding is about N. 45° E. The dip of the beds is about 55° SE. at the breccia zone, so that the fault clearly cuts the bedding at a moderately sharp angle. The hanging-wall dolomite is greatly brecciated through a zone nearly 50 feet wide; the brecciation terminates abruptly at the smoothly polished fault surface, and the ore bodies are thus confined to the hanging-wall block. Miser's observations[26] indicate a zone of rich ore about 6 feet wide adjacent to the fault surface, and lower-grade ore through the rest of the breccia zone.

Evanston District.—Several prospects a few miles southwest of Sneedville and north of the Clinch River constitute the Evanston district (Fig. 1). So far as the writer knows, there has been no production of zinc ores here, although considerable money has been spent in attempted development. The deposits are of interest because they occur in a bed of magnesian limestone within the Rome formation. Mineralization as indicated by the scattered prospects was apparently limited to the top of a limestone bed and, at one place at least (Givens prospect[27]), was confined to a thin zone just below an impervious shale bed. A regional overthrust passes through the district, and apparently the prospects are for the most part closely related in position to this fault or to local crumpling and brecciation of beds in a minor anticline on the south limb of the major anticline of the region.

[25] Keith, Arthur: *Op. cit.*, Maynardville folio.
[26] Purdue, A. H.: *Op. cit.*, p. 52.
[27] Secrist, M. H.: *Op. cit.*, pp. 57–58.

Embreeville District.—This district lies in Bumpas Cove, 10 miles south of Jonesboro (Fig. 1). The country rock of the ore bodies is dolomite of the lower part of the Shady dolomite, in the surface zone of which oxidized ores have been concentrated. Sphalerite and galena are present in the underlying dolomite beds but have so far played a negligible part in the district's production. According to Keith's map [28] Bumpas Cove is underlain by an open syncline in the Shady dolomite, which is exposed by the partial erosion of an overthrust block of Lower Cambrian quartzite. The syncline is itself part of an overthrust block. In this region, therefore, deformation by folding and shearing, with attendant brecciation, has been great.

Felknor Mine.—The structural conditions at the Felknor mine (now abandoned) as described by Miser [29] and Secrist [30] are worthy of brief mention. The mine is in Jefferson County, about 12 miles east by south of Jefferson City (Fig. 1). The country rock is the upper part of the Knox dolomite. The mineral body, containing sphalerite and galena, occurs in southeastward-dipping beds in a breccia which follows a vertical fault plane that strikes N. 60° E. and displays horizontal slickensides. The brecciation is more intense on the northwest side of the fault. According to Miser, "the extremely brecciated part of the rock is at least 200 feet long and 75 feet wide, but fracturing of the magnesian limestone prevails over a much larger area." The ore body has been prospected for nearly 500 feet along the fault. Secrist notes that mineralization does not follow the entire width of the brecciated zone, and is greatest where minor breaks, which strike N. 60° W., extend from the fault into the breccia. He reports that chalcopyrite is present.

Other Districts.—Space does not permit a review of the remaining districts in which zinc prospects are found, but in general the conditions reported indicate relations between faulting or folding, brecciation, and mineralization similar to those described for the more important districts already mentioned.

[28] Keith, Arthur: U. S. Geol. Survey, Geol. Atlas, Roan Mt., folio 151, 1907.
[29] Purdue, A. H.: *Op. cit.*, pp. 56–57.
[30] Secrist, M. H.: *Op. cit.*, pp. 147–151.

ORE-BEARING BRECCIAS.

Types of Breccias.—The ore-bearing breccias of the southern Appalachian districts as observed on the surface and in the extensive underground workings of the active mines are of two general types—rubble breccias and shatter, or "crackle," breccias. Bodies of each have been sites of ore deposition. The shatter type is the more extensive. Both are ordinarily healed by coarsely crystalline white dolomite, which has also been fractured in places and partly replaced by sphalerite (Fig. 9).

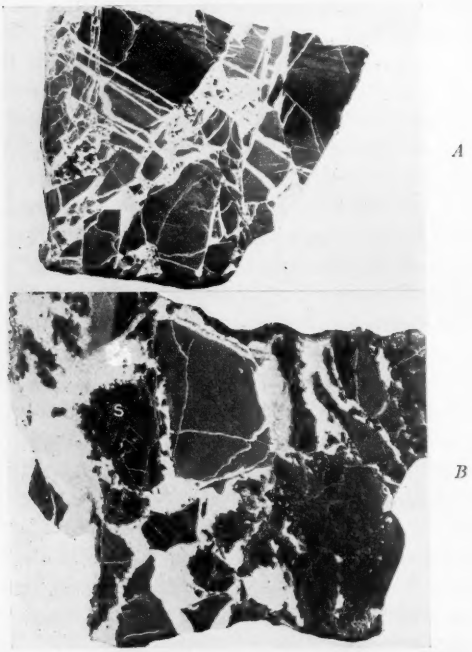

FIG. 9. Breccias from ore zone, Jefferson City, Tennessee. Rock fragments are dolomite. Coarse white ("gangue") dolomite as matrix and in veinlets crossing rock fragments is replaced by sphalerite (S). *A*. Illustrates slight displacement of fragments, a feature common to more highly shattered breccias in and close to richer ore bodies. *B*. Rich ore.

The shatter breccias are composed of sharply angular fragments and blocks that show very little relative displacement or rotation. It is characteristic, therefore, that most of the adjacent fragments show matching boundaries. These breccias grade texturally into jointed country rock or into rubble breccia. This description is in general accordance with Norton's definition of "crackle breccia."[31] The zone of transition between shatter and rubble breccias might well correspond with his "mosaic breccia," but such a designation is unsatisfactory because it suggests a distinct type, rather than a transitional type that partakes of the textures of both shatter and rubble breccias.

In the rubble breccias there has been a marked degree of relative displacement of fragments and commonly some degree of rounding. Also, the fragments are small and comparatively uniform in size. For the most part such breccias indicate crushing in a fault zone. However, the designation of a breccia as "rubble" is determined largely by texture rather than by recognition of a fault zone to which it is supposedly related, as in the thick dolomite beds of this region narrowly restricted key horizons are not recognizable. In many places, also, much of the faulting has occurred in a direction parallel to the bedding as many slight displacements through a zone rather than as a single displacement along a surface. Where a thin zone of dolomite rubble breccia overlies a comparatively unbrecciated thin bed of limestone, the movement may have taken place at the contact. At the Austinville mine it is reported that under the ore zones at several places planes of movement have been found parallel to the bedding; the open pits also display minor fissures nearly parallel to the bedding. At the New Prospect mine shear planes parallel to the bedding and showing polished and grooved surfaces are numerous and prominent.[32] This type of adjustment to thrust forces is a necessary result in the folding of a thick series of competent beds and is considered to be the cause of the formation of some of the rubble breccias.

[31] Norton, W. H.: A Classification of Breccias. Jour. Geology, vol. 25, p. 160, 1917.

[32] Miser, H. D.: See Purdue, A. H., *op. cit.*, pp. 45–46.

Mode of Origin of Tectonic Breccias.—It is probable that in a thick competent series composed of dolomite and limestone beds in which dolomite predominates and which is under great cover, the greater brittleness of dolomite and the greater ease of flowage of limestone beds would tend to localize brecciation in the dolomite rather than in the limestone. This would seem to be true particularly in the early stages of deformation by compressive stress. Early in the thrust epoch there would accordingly be a general shattering ("crackling") of brittle beds which, though active through a thick zone, would nevertheless seek and tend to follow the weakest of the brittle beds. Thus brecciation in the early stages would take place roughly parallel to the bedding and coincident with some of the necessary adjustment that occurs during folding by the slippage of strata along bedding planes. Later, of course, thrust faulting would develop across the bedding, at a sharp angle to it where dips were still low, or even following the bedding direction in places, but ultimately would cross the beds near the crests and troughs of folds. Hence in areas of low dips there may actually be a local conformation of breccia zones to a definite horizon.

Relatively thin bodies of rubble breccia are formed by actual slippage within the thick shatter zones of early brecciation. The stress is at first distributed through a relatively thick zone but later manifests itself chiefly by thrusting in the weakest zone. Shattering of the country rock is promoted further by torsional flexing, or indeed by any form of local warping. Undistributed thrust forces will tend to produce deflections of the fold axes, cross shearing as sheeting or "slicing," and tear faults, all three of which may be regarded as of the same type of deformation, and all of which contribute to the formation of local intensely brecciated zones in the general area of thrusting and brecciation.

With more intensive folding, more widespread brecciation would result, and consequently less stratigraphic limitation of the breccia zones. The much sharper folding of the Austinville-Ivanhoe region, as compared with the Mascot-Jefferson City district, would easily account for thicker or more numerous breccia

zones in the Shady dolomite. The overlying formations—Rome and Elbrook—were likewise brecciated and are slightly mineralized in a few places, but in general, while affording breccia beds as possible sites of deposition, they were not reached by adequate channels of access for ascending solutions through the thick shale beds of the Rome.

If the breccias that carry the ores had been formed by the collapse of solution caves, the extensive underground workings at Mascot and Jefferson City should provide evidence in the form of solution and depositional features characteristic of caves and their deposits. Numerous vugs and other open cavities, a rounding of fragments, great variation in size of fragments, general displacement of fragments, a matrix filling of "cave earth" and characteristic depositional or residual materials, and widening of joints by solution in the roof areas should be indicated. Such evidences are entirely lacking. The gradations from unbrecciated into highly brecciated rock, as described for the Mascot mine, militate strongly against the cave theory of origin.

ORIGIN OF THE DEPOSITS.

It is not strictly within the intended province of this paper to discuss the source of the mineralizing solutions. However, a few statements regarding this interesting aspect of the subject may not be entirely unwarranted.

That the zinc deposits of the southern Appalachian region were precipitated from meteoric waters, either of downward or of artesian circulation, is the theory that has been expounded by most of the previous writers on the subject and is commonly held today. According to this theory, the metals were derived from the pre-Cambrian rocks of Appalachia, were dissolved in the Cambrian and Ordovician sea water, and became incorporated in the sediments that were deposited in the Appalachian trough during these periods. From this widely disseminated state the ore minerals were concentrated in favorable channels by circulating ground waters of meteoric origin. Breccia zones either of tectonic or of cave-collapse derivation provided well-defined paths for active circulation.

The theory that downward-circulating meteoric waters deposited the ores should be rejected because of the proved depth to which the deposits extend without general change in mineral content, and their lack of relation to base-levels, past or present. Moreover, it is difficult to conceive of the mechanism by which stratigraphic, lithologic and geographic selectivity were so clearly followed under conditions of such wide dispersal, both areal and stratigraphic, of the assumed source minerals in the original sediments, and by waters of a circulation that is characteristically not selective with respect to available openings in the superficial zone of fracture and solution.

The possibility of deposition from an artesian circulation cannot be so easily dismissed. There is difficulty, however, in adapting the structural and stratigraphic relations of the ore bodies, their extent along the dip of the beds, and their limitations along the strike, to the requirements of such a theory. By the same token, the gathering of mineral content from its widely dispersed condition seems inconsistent with the type of structural control exercised in the deposition of the ore deposits so clearly indicated at several places in the Valley.

Nason,[33] on the other hand, believed that the mineralizing solutions were of deep-seated origin, possibly connected with intrusive rocks.

The form and structural relations of the deposits are such as to be satisfactorily explained by a theory of hypogene circulation rising from considerable depth along deeply extending cross-fracture zones. Except by inference, however, there is a lack of igneous phenomena of appropriate age in proximity to the zinc belt to which connection with the deposits can be ascribed.

An analogous example of this type of structural control is described for the Goodsprings area, Nevada, by Hewett.[34] Here large tabular deposits occupy breccia zones formed by thrust faults, and to a large extent the ore bodies are parallel or nearly

[33] Nason, F. L.: Zinc Deposits of Eastern Tennessee. Eng. and Min. Jour., vol. 99, p. 734, April 24, 1915.

[34] Hewett, D. F.: Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada. U. S. Geol. Survey, Prof. Paper 162, pp. 57–67, 1931.

parallel to the bedding of the partly dolomitized country rock in which they occur. Cross faults of later origin than the thrust breccias were the mineralizing fissures.

Perhaps a suggestion of zonal arrangement is to be derived from the localization of galena, fluorite, and relatively dark-colored sphalerite at three or four places in the Valley, and of lighter-colored sphalerite without galena and fluorite at the mines and prospects that are distributed widely around these points. Galena is prominent at Austinville, and much of the sphalerite is of darker color than in outlying areas. Fluorite is present in small amount. In the Cedar Springs district the very light-colored sphalerite occurs with a slight amount of fluorite and no galena. The mine of the Rye Valley Mining Company at Sugar Grove produced only galena concentrates; fluorite is prominent, but sphalerite was found only at the 200 level. Outlying prospects in the Sugar Grove district, with the exception of the Martin prospect, show no galena. The Martin prospect, 3 miles southeast of Adwolf (Fig. 3), shows darker sphalerite and a little galena. Brow[illegible] has indicated a distinct zonal arrangement at Austinville as regards the Fe: Pb, Fe: Zn, and Zn: Pb ratios vertically along the cross fissures and horizontally outward from these fissures, with lead concentration decreasing with depth. The relative distribution of dark and light sphalerite in Virginia is broadly analogous to some of the zonal features in the Leadville district, Colorado, according to Loughlin and Behre.[36]

CONCLUSIONS.

The writer believes that the zinc deposits of the southern Appalachian province were accumulated in breccias of tectonic origin by ascending hypogene solutions. The brecciation was brought about by overthrusting and connected phenomena, and the formation of the breccia bodies was particularly favored by local cross fracturing, minor warping, and deflection of fold axes.

[35] Brown, W. H.: Paper before XVI Internat. Geol. Congress, Washington, July, 1933.

[36] Loughlin, G. F., and Behre, C. H., Jr.: Zoning of Ore Deposits in and Adjoining the Leadville District, Colorado; ECON. GEOL., vol. 29, pp. 215–254, 1934.

The textural characteristics of the breccias, their occurrence at numerous horizons without close relations to old erosional surfaces, and the great depths at which they were formed, preclude an origin by collapse of caverns. They were apparently developed during the period of Appalachian orogenic deformation.

The paths of access for the mineralizing solutions were either the deeply extending thrust breccia zones, or the later-formed cross fissures, such as are found at Austinville, Ivanhoe, and elsewhere. The directness and continuity of cross fissures favor them as feeding channels. Solutions rising along such fissures would thus spread laterally through the several zones of thrust breccias encountered and permit concentration of minerals in the situations in which they are now observed. Consequently, structural as well as stratigraphic geology is of exceptional assistance to the operator engaged in prospecting and developing the zinc areas of the southern Appalachian region.

U. S. Geological Survey,
Washington, D. C.

THE DUMORTIERITE–ANDALUSITE MINERALIZATION AT OREANA, NEVADA.

PAUL F. KERR AND PHILLIP JENNEY.

INTRODUCTION.

In the recent discussions of the occurrence and origin of the aluminous silicates, andalusite, cyanite and sillimanite, appearing in this journal,[1] little notice has been taken of the somewhat less common but related mineral, dumortierite. It is the purpose of this paper to record data concerning dumortierite, particularly as it concerns the unusual mineralization near Oreana, Nevada. The abundance of andalusite occurring with the dumortierite is believed to have special significance, the andalusite having an important bearing on the early history of the deposit. Although a general description of the mineralized area was published several years ago by the Nevada Bureau of Mines,[2] recent studies have developed additional field and microscopic data relating to the origin of the deposit.

The dumortierite deposit is situated on the west side of the central portion of the Humboldt Range about five miles east of Oreana, Nevada. The property is owned by Champion Sillimanite, Inc., and is located in the upper part of Humboldt Queen Canyon a few hundred yards from the northwestern corner of the area included in the geologic map of the Rochester Mining District.[3]

[1] Dunn, J. A.: Andalusite in California and Kyanite in North Carolina. ECON. GEOL., vol. 28, no. 7, pp. 692–695, November, 1933. Kerr, Paul F.: The Occurrence of Andalusite and Related Minerals at White Mountain, California. ECON. GEOL., vol. 27, no. 7, pp. 614–643, 1932. Stuckey, J. L.: Cyanite Deposits of North Carolina. ECON. GEOL., vol. 27, pp. 661–674, 1932.

[2] Jones, J. Claude: The Geology of the Deposit of Dumortierite in Humboldt Queen Canyon, Pershing County, Nevada. Nevada Univ., Bull., vol. 22, no. 2 (Mackay School of Mines, Bull. on Dumortierite), pp. 23–26, March 15, 1928.

[3] Knopf, Adolph: Geology and Ore Deposits of the Rochester District, Nevada. U. S. Geol. Surv., Bull. 762, 78 pp., 5 figs., 4 pls. (incl. map), 1924.

The dumortierite-andalusite mineralization has been concentrated along two parallel zones in a quartz-sericite schist in which occur irregular lenses of andalusite, partially or entirely altered to dumortierite. These zones are about 75 feet wide and are separated by several hundred feet of largely barren schist which is essentially a quartz-sericite mixture (Fig. 1). A large part of the ore has been taken from open cuts. At one time underground operations were carried on from a tunnel 600 feet in length, but the tunnel has been abandoned. Many small veins of quartz and dumortierite occur in a zone continuing along the strike of the deposit for several miles, but thus far these have proved too low-grade to be of economic importance.

According to Riddle,[4] over 2500 tons of dumortierite ore have been mined at this locality, the only producing property of its kind. It is used in the manufacture of spark plug cores and chemical laboratory porcelain. Its behavior on heating, due in a large measure to its boron content, is particularly valuable in the manufacture of high-grade refractory porcelain. As in the case of the aluminous silicates andalusite, cyanite and sillimanite, the mineral dumortierite may be changed to mullite by calcination.

The senior author, in the course of several visits to the deposit during the past three years, has had an opportunity both to study the deposit and to collect mineralogical and petrological suites of specimens, which have been augmented by specimens furnished by Champion Sillimanite, Inc. During the summers of 1932 and 1933 the junior author mapped and studied some 40 square miles of the central Humboldt Range in connection with a broader study of the geology and ore deposits, an account of which is now being prepared for publication.

The writers wish to acknowledge the courtesy of Dr. Joseph A. Jeffery, President of Champion Sillimanite, Inc., who has coöperated by allowing the use of the camp facilities at the mining camp near Oreana and has made available information regarding

[4] Riddle, Frank Harwood: Mining and Treatment of the Sillimanite Group of Minerals and Their Use in Ceramic Products. Amer. Inst. Min. Met. Eng., Tech. Pub. No. 460, Class H, Nonmetallic Minerals, No. 20, February, 1932.

the deposit. We are also indebted to Mr. C. D. Woodhouse, General Manager, for his kindness in pointing out the various mineral associations at the mine and for outlining the details of operations. Thanks are also due to Mr. J. M. Cole, Superintendent, for assistance and information.

GENERAL GEOLOGICAL RELATIONS.

The Lower Triassic of the central Humboldt Range consists of an extensive series of lavas and tuffs ranging in composition from rhyolite to keratophyre.[5] In the vicinity of the dumortierite mine two extrusive units have been recognized, the Weaver rhyolite and the Rochester trachyte. These are separated by metamorphosed and highly schistose tuffs and pyroclastics which, in the field mapping, have been included with the younger Weaver rhyolite as the base of that series. Highly deformed Middle Triassic limestone strata border the valley toward Oreana and are separated from the Weaver rhyolite on the east by a fault of the Basin and Range type, as described by Louderback.[6] A generalized geologic section extending east-west and showing the outstanding features from the edge of the valley floor to the dumortierite deposit, is shown in Fig. 1.

About four miles north of the mineralized area large masses of quartz monzonite and granite porphyry have been intruded into the Triassic extrusives. Off-shoots from this mass approach within approximately one mile of the deposit on the northeast. This igneous material has invaded and metamorphosed the earlier flows and tuffs, giving rise to many dikes and later veins which invade the surrounding rocks. Mineralizing solutions are believed to have had their source in this magmatic activity and to have invaded the tuffaceous rocks, producing andalusite and dumortierite.

Jones[7] describes the dumortierite as occurring in two zones 50 and 75 feet wide which strike east of north and dip west. The

[5] Knopf, Adolph: *Op. cit.*

[6] Louderback, George Davis: Basin Range Structure of the Humboldt Region. Geol. Soc. Amer. Bull., vol. 15, pp. 289–346, pls. 14–21, July 15, 1904.

[7] Jones, J. Claude: *Op. cit.*

original character of these zones and of the surrounding schists was not definitely determined. New data seem to indicate that most of the surrounding schists were originally pyroclastics and that the two zones containing the andalusite and dumortierite were tuff beds within the series.

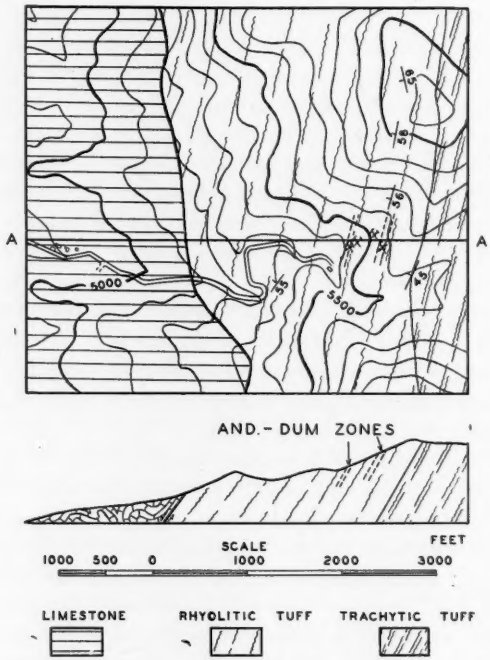

FIG. 1. Geologic sketch map of Humboldt Queen Canyon, Humboldt Range, Nevada, showing location of dumortierite mine.

Jones also mentions many outcrops of massive quartz. The most prominent of these is a pure white, vitreous quartz mass occurring about 2,000 feet north of the main dumortierite deposit, and also in the tuff horizon. This is cut by small veins of blue and pink dumortierite and seems to be similar, in a general way,

to the quartz segregation occurring at White Mountain, California.[8]

MINERALS OF THE DEPOSIT.

Dumortierite is the outstanding mineral of economic importance. Associated with it are considerable concentrations of andalusite. Quartz, albite and sericite also occur. In addition, minor amounts of titanite, rutile, leucoxene, zircon, magnetite, pyrite, limonite, tourmaline, biotite and vein carbonate occur in various parts of the mineralized zone.

Dumortierite.—Dumortierite occurs in three generations: (1) as coarse, euhedral, blue crystals; (2) as matted lavender or pink masses; (3) as fibrous pink veins or isolated pink crystals. Most of the ore mined consists of dumortierite of the second generation. Criteria for recognizing the three generations may be observed both in thin section and in the field relations. Remnants of blue dumortierite (first generation) occur within matted masses of the second generation of dumortierite. Pink veins of fibrous dumortierite, varying in size from microscopic thickness up to two inches, cut both previous generations. Sericite and quartz accompany the early euhedral blue crystals as well as the matted lavender ore masses.

In Fig. 2, both the first and the second dumortierite generations are represented. As observed in thin section, thin blue crystals of the first generation border and penetrate andalusite grains, while both are residual in the massive, matted, second generation of dumortierite. The more coarsely crystalline form of the first generation is illustrated in Fig. 3. The fibrous pink dumortierite of the third generation frequently contains associated quartz. Needles of dumortierite may be dispersed through quartz in such a way that the quartz becomes pink, resembling rose quartz (Fig. 4). Dumortierite of each generation is associated with andalusite in such a way that it appears to be later than andalusite (Fig. 5).

The mineralogy of dumortierite has been summarized by O.

[8] Kerr, Paul F.: *Op. cit.*

R. Grawe.[9] X-ray data and a summary of its behavior under heat treatment have been published by Bowen and Wyckoff.[10]

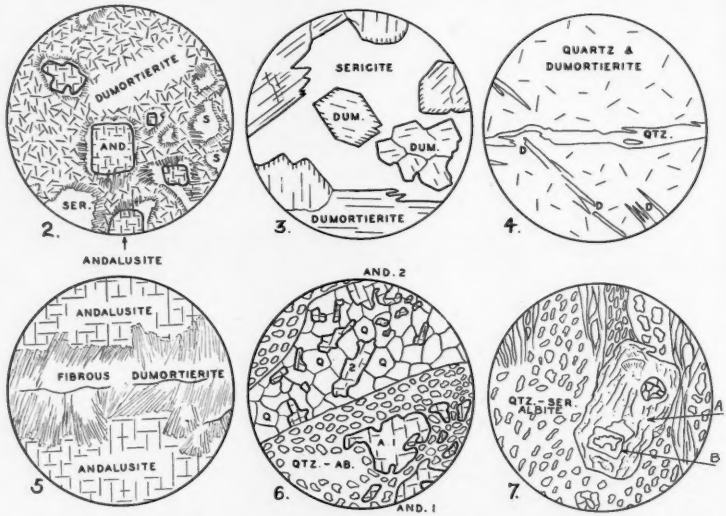

FIG. 2. Blue dumortierite crystals surrounding and penetrating earlier andalusite remnants and followed by massive, matted dumortierite. × 10.

FIG. 3. Coarsely crystalline blue dumortierite of the first generation, showing pseudo-hexagonal outlines. × 10.

FIG. 4. Fine acicular needles of dumortierite in quartz. × 10.

FIG. 5. Fibrous dumortierite vein penetrating and replacing andalusite. × 10.

FIG. 6. Portion of a vein containing second andalusite cutting quartz-albite mass containing first andalusite. × 10.

FIG. 7. An example of a devitrified and invaded tuff. *A*, devitrified groundmass; *B*, albite phenocryst. × 10.

X-ray diffraction measurements of the mineral from Oreana agree closely with those recorded by Wyckoff.

[9] Grawe, O. R.: The Mineralogy of Dumortierite. Nevada Univ. Bull., vol. 22, no. 2 (Mackay School of Mines, Bull. on Dumortierite), pp. 7–22, March 15, 1928.

[10] Bowen, N. L., and Wyckoff, R. W. G.: A Petrographic and X-ray Study of the Thermal Dissociation of Dumortierite. Jour. Wash. Acad. Sci., vol. 16, no. 7, pp. 178–189, 1926.

Andalusite.—Andalusite occurs in disseminated grains scattered throughout the mass of the schistose rock. In parts of the two mineralized zones the concentrations, in the shape of irregular lenses, are large enough to raise the question whether it constitutes an economic deposit in itself. In any event it would seem that, in view of the rather high specific gravity (3.16–3.20) in relation to the quartz and muscovite with which it is associated, and the granular habit in contrast to the fibrous character of the dumortierite, a process of concentration might be worked out for the recovery of the andalusite alone.

Two generations of andalusite may be observed in thin sections: an early generation in a fine quartz and albite matrix, and a later generation of fresher appearance and associated with vein quartz (Fig. 6). Vein andalusite may have been derived from the earlier by the invading solutions. Both generations occur prior to the crystallization of dumortierite.

Quartz.—Quartz is the most common mineral in the deposit, occurring with both the andalusite and the dumortierite, and in each of the later stages of mineralization. Too much quartz with dumortierite lowers the quality of the ore, and is removed as far as possible by hand sorting.

Albite.—Albite is abundant in the vicinity of the deposit, especially throughout the Triassic tuffs and flows. The penetration of quartz and albite, derived, in all probability, as an end-stage product of the igneous activity which produced the quartz monzonite and granite porphyry masses to the north, appears particularly widespread. The tuffs were apparently considerably invaded by solutions forming quartz and albite (Fig. 7).

Sericite.—Non-elastic, dense or fine scaly white mica is abundant. X-ray patterns of this material agree with muscovite, and commercial analyses reported by the Champion Porcelain Company indicate that it is almost entirely a potash mica—sericite. It occurs with dumortierite and in the adjacent country rock. It is assumed that the sericite marked the hydrothermal stage of mineralization.

Masses of sericite and quartz occur close to the andalusite-

dumortierite zones. The sericitic concentrations appear to be localized in certain tuff horizons, possibly due to the original composition of the layer. Sericite is, however, of widespread occurrence, minor amounts being seen in almost every thin section of both country rock and ore examined.

ROCK TYPES.

Complexly folded middle-Triassic limestone strata are down-faulted against the Weaver rhyolite on the west (Fig. 1). These strata are apparently unrelated to the ore deposition.

The Weaver rhyolite contains important tuffaceous phases. These tuffs are rhyolitic and make up most of the zone containing the mineralized area, although a few minor intercalated flows may also be present in the tuff series. The tuff series as a whole has been highly altered and sheared, so that at present it is composed largely of schists and quartz-sericite masses. The old tuffs are generally white on fresh fracture, but commonly weather to a light brown color due to oxidation of disseminated pyrite. Under the microscope, the schistosity is seen to have resulted in the directional lengthening of angular relict outlines, signifying early glassy patches and broken quartz and feldspar crystals around which sericite is aligned and wrapped (Fig. 7). Although for the most part metamorphism has brought about a change in mineralization, relict outlines of feldspar phenocrysts indicate the original igneous-extrusive character of the rock. In places an irregular texture has been imparted to the schist by the later penetration of albite, quartz and sericite, chiefly as a mosaic groundmass and rarely as small phenocrysts. Later mineralization introduced not only sericite but minor amounts of titanite, rutile, zircon, magnetite, pyrite, tourmaline, and biotite, together with quartz.

The underlying tuffs of the Rochester trachyte strongly resemble the rhyolitic variety, differing chiefly in having fewer quartz phenocrysts and a somewhat darker color. The trachytic flows are commonly finely banded with alternating dark and white layers, and show flow structure. As a whole, the trachytic and

rhyolitic tuffs are so similar megascopically that it is difficult to distinguish between them in the field.

Both the quartz monzonite and the granite porphyry, which compose the igneous massif to the north, from which the mineralizing solutions apparently emanated, show evidences of extensive albitization. In the monzonite, fresh unaltered albite and quartz are abundant, the older feldspars generally showing a rim of the fresher albitic material. The porphyry carries phenocrysts of fresh albite and quartz and is cut in places by veins of albite-quartz.

The andalusite-dumortierite lenses west of the main workings are cut, at depth, by a later diabase dike which is unrelated to the mineralization. This dike appears in the underground workings, although no outcrop can be seen at the surface. It is fine-grained to dense, and consists of minute matted labradorite laths with interstitial augite and magnetite.

SEQUENCE OF MINERALIZATION.

Pneumatolytic Stage.—The andalusite-dumortierite mineralization appears to have occurred in two stages. An earlier pneumatolytic stage, resulting in the andalusite concentration, occurred during, and as a direct result of, the intrusion and crystallization of the large masses of igneous material to the north. A later hydrothermal stage accompanied the cooling of the magma and gave rise to the extensive areas of fibrous or matted dumortierite and sericite. The separation of the processes of mineralization into two stages is indicated by the replacement criteria observed both in thin sections and in the megascopic features of the ore. However, the transition between the two processes was gradual and no sharp line of demarcation appears to exist.

After the deposition of the tuffs and the extrusion of the flows during early Triassic time, the beds were folded and sheared. Shearing aided the devitrification of the various glassy portions to a quartz mosaic, and the accompanying deformation produced the rather high westward angle of dip of the series (Fig. 8). The cessation of magmatic intrusion was marked by a permeation

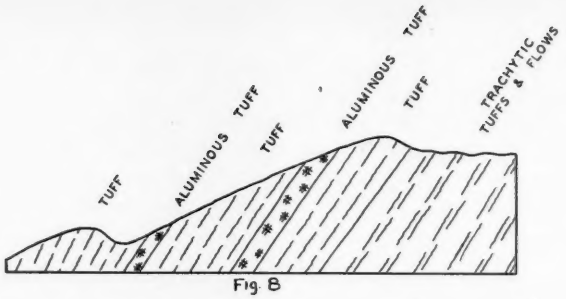

Fig. 8

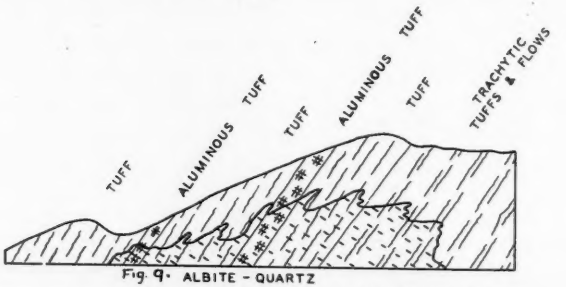

Fig. 9. ALBITE - QUARTZ

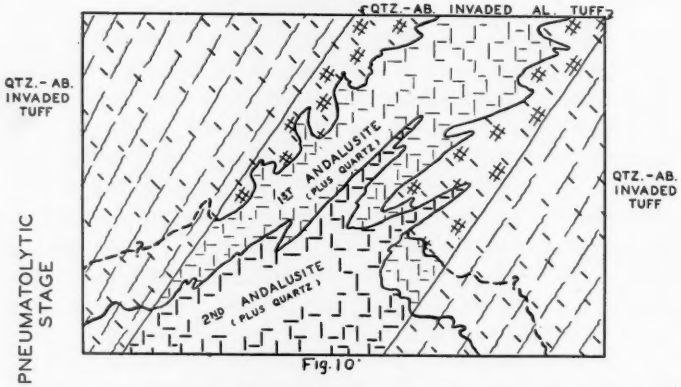

Fig. 10.

FIG. 8. Enlargement of part of Fig. 1, showing aluminous tuff zones before mineralization took place.

FIG. 9. Diagram illustrating the quartz-albite permeation shown in Fig. 8.

FIG. 10. Representation of the two andalusite-quartz concentrations along the aluminous tuff zones.

of the country rock, especially the tuffs, by quartz-albite end-stage material (Fig. 9). This material apparently emanated from the large area of quartz monzonite and granite porphyry to the north.

Closely following, or perhaps at the same time as the albitization, the andalusite and quartz concentrations occurred along distinct zones in the rhyolite tuff (Fig. 10). It is not apparent whether the albitization and the andalusite concentration were separated or simultaneous. Two distinct concentrations of andalusite and quartz took place, as shown by the older and younger generations illustrated in Fig. 6. The reason for the occurrence of andalusite in lenses restricted to two distinct zones is uncertain but it appears probable that the original composition of the two tuff layers was the controlling factor.

During the early pneumatolytic stage rutile, zircon, titanite, tourmaline, biotite, magnetite and pyrite were being developed in the country rock, which was also considerably recrystallized. These products of igneous activity are not entirely confined to the country rock, but may be found in places in the andalusite masses.

It does not appear that the alumina was introduced, but rather, that andalusite was formed by recrystallization from aluminous material already present in the tuff beds. The large quartz mass in the tuff zone to the north and the presence of large amounts of quartz in the deposit would be difficult to explain if direct crystallization of excess alumina from a magma were postulated. Both the occurrence and nature of the minerals produced during this early stage seem to indicate an aqueous-igneous and pneumatolytic influence, due to the proximity of an igneous body.

Hydrothermal Stage.—After the igneous activity had passed its peak, there was a resultant dying out of the pneumatolytic action. The solutions apparently became increasingly charged with boron and water vapor, and the mineralizers acting under the influence of the lower temperature conditions which prevailed produced the minerals dumortierite and sericite.

Dumortierite first appeared as large blue euhedral crystals replacing the andalusite and accompanied by sericite (Fig. 3).

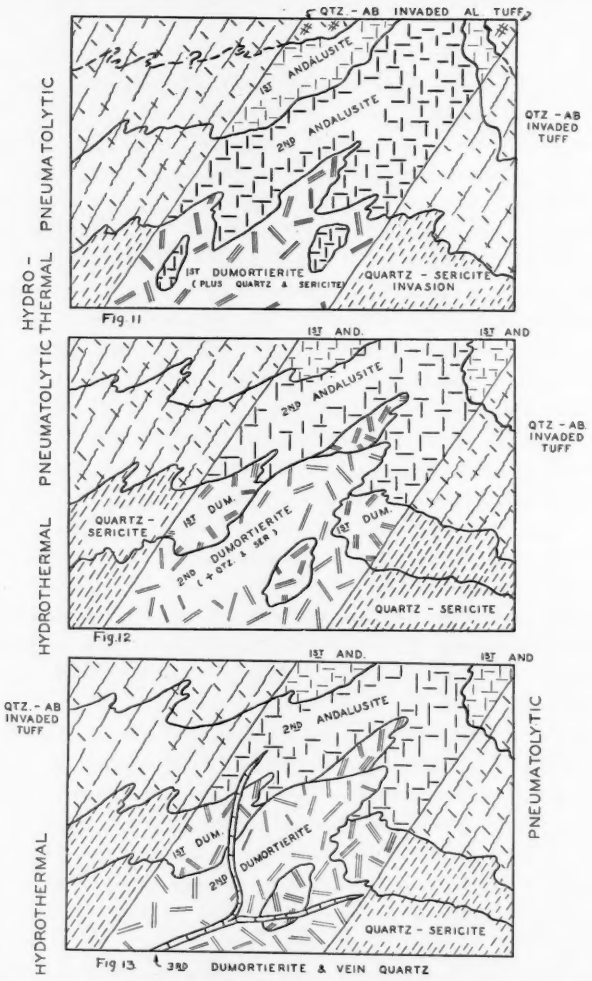

FIG. 11. Diagram of early invasion of blue dumortierite, quartz and sericite, showing dumortierite replacing earlier andalusite.

FIG. 12. Sketch depicting the invasion of second generation of dumortierite during main period of hydrothermal mineralization.

FIG. 13. Idealized diagram of fibrous, third-generation dumortierite and quartz veins cutting earlier minerals of the deposit.

This probably marked the end of the pneumatolytic stage and the beginning of the hydrothermal. The sericite occurs both interstitially and as an alteration of feldspar. Quartz was also present in this mineralization (Fig. 11). Small amounts of blue dumortierite were also distributed sparsely through the tuff zone.

Closely following the early blue dumortierite, the main hydrothermal mineralization of matted pink dumortierite invaded and replaced andalusite lenses (Fig. 12). This action is illustrated in Fig. 2, which shows isolated remnants of andalusite in a groundmass of matted pink dumortierite. Surrounding and penetrating the andalusite remnants are fringes of coarse euhedral blue dumortierite crystals with interstitial sericite. The pink dumortierite was also accompanied by quartz and sericite and by a continuation of the quartz-sericite invasion of the country rock. Crystals of pink dumortierite were also formed sparsely throughout a large surrounding area.

The closing chapter of igneous activity was marked by the appearance of narrow veins, not over two inches in width, of fibrous pink dumortierite and quartz (Figs. 5, 13). These cut the earlier formed minerals of the deposit in all directions and are of interest because of the high degree of purity of the dumortierite. The mineralization terminated with barren quartz veins (Figs. 8–13).

SUMMARY.

Both field and petrologic evidence point to the following sequence of events in the history of the andalusite-dumortierite deposit at Oreana, Nevada.

1. Deposition of a series of rhyolitic and trachytic tuffs with some intercalated flows.

2. Intrusion of an adjacent igneous mass accompanied by shearing, devitrification and alteration of the tuff series.

3. Invasion of volcanics by quartz-albite end-stage material from the near-by igneous source. This was either accompanied or closely followed by a concentration of andalusite and quartz along restricted zones in the tuffs. This phase of the mineralization was pneumatolytically controlled.

4. Hydrothermal mineralization involving the replacement of the earlier andalusite lenses by dumortierite occurred in three closely connected stages resulting in:

(1) Coarse euhedral crystals of blue dumortierite.
(2) Matted lavender or pink masses.
(3) Fibrous pink veins or isolated pink crystals.

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DIFFERENTIATION IN TRAPS AND ORE DEPOSITION.

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INTRODUCTION.

A STUDY of differentiation in Keweenawan lava flows of the Michigan copper district has been carried on as a part of the copper and iron research program of the Michigan College of Mining and Technology. Funds for the necessary rock analyses were provided by a grant from the Geological Society of America.[1] The work is a continuation of studies made by the Calumet and Hecla geological department, the company contributing drill core and data from its files.

The rock analyses include copper and sulphur determinations to three decimal places. These furnish new and reliable data concerning the amounts of copper and its distribution in the traps. The purpose of this paper is to present the new information and to point out its bearing on the theories of copper deposition. The transportation of elements in the gaseous state, as brought out in these studies, will be briefly discussed.

ORIGIN OF THE MICHIGAN COPPER DEPOSITS.

There are two general theories as to the origin of the Michigan copper deposits. One, by Dr. A. C. Lane, considers the copper as having been leached from the traps by descending salt waters, and precipitated in permeable channels by the reducing action of the ferrous iron of the amygdaloids and conglomerates. The other theory, developed by Calumet and Hecla and by United

[1] The writers' paper on "Differentiation in Lavas of the Michigan Keweenawan," submitted to the Geological Society of America, presents complete analyses of the rocks referred to in the present paper. A discussion of the differentiation of the lavas, with numerous diagrams, presents material which will be of interest to those who wish to follow up this subject, only briefly touched upon in the present paper.

States Geological Survey geologists, considers the copper to have been introduced in ascending magmatic solutions from great depths and precipitated in permeable channels by the oxidizing action of the ferric iron of the amygdaloids and conglomerates.

In discussing the origin of these deposits, Lindgren [2] suggests modifications of these two theories which include some features of each. Although he does not propose a definite theory, he makes several suggestions, the substance of which is as follows: Ascending magmatic waters with a "very liberal mixture of meteoric water" dissolved a large amount of the primary copper disseminated in the traps. These waters carried chlorides, and the precipitation of the copper was, in part, according to the Ferneke reaction as postulated by Lane. This reaction is essentially a reduction of oxidized copper salts in solution by the ferrous oxide of the amygdaloid or conglomerate lodes. The two theories have been discussed from various angles; [3] and from the standpoints of source of copper, method of transportation, and chemistry of deposition, the ascending magmatic water theory outlined seems most competent to explain the facts of occurrence.

COPPER CONTENT OF THE FLOWS.

All the common types of lava flows in the district were carefully sampled and analyzed. The flows selected were chosen as being the freshest and most typical examples obtainable. The method of sampling in most cases was to make a composite by taking chips of uniform size at uniform intervals in the diamond drill cores. Twelve basaltic rocks, three quartz porphyries, and three phases of the Mount Bohemia gabbro were analyzed. The copper and sulphur assays are as follows, the rock names being those used in the literature of the district.

The arithmetical average of all of these is sulphur 0.013% and copper 0.011%. Perhaps it would be better to omit from the average some of the duplications of the more uncommon trap

[2] Lindgren, Waldemar: Mineral Deposits, p. 525. McGraw Hill, New York, 1933.

[3] Butler, B. S., and Burbank, W. S.: The Copper Deposits of Michigan, U. S. Geol. Surv. Prof. Paper 144, pp. 118–142, 1929.

	Sulphur per cent.	Copper per cent.
Ophite	0.010	0.008
"	0.023	0.012
"	0.008	0.009
Feldspathic melaphyre	0.010	0.024
Glomeroporphyrite	0.015	0.022
Fine-grained glomeroporphyrite	0.008	0.002
Fine-grained melaphyre	0.012	0.003
" " "	0.014	0.023
" " "	0.018	0.038
" " "	0.014	0.003
Porphyrite	0.015	0.002
"	0.012	0.003
Felsite	0.011	0.003
"	0.010	0.003
"	0.006	0.003
Gabbro-aplite	0.008	0.013
Gabbro	0.030	0.010
"	0.011	0.014

types, all of the felsites, the gabbro group, and the trap which assays 0.038% copper. The latter is the "Ashbed" trap, the amygdaloid of which is one of the copper-bearing lodes of the district and in the core samples has visible introduced copper. This leaves the first seven listed above, and the first one of the "porphyrites," for use in calculating an average. To include three ophites in the list is proper, inasmuch as ophites are the predominant rocks of the region. The average of these eight samples is sulphur 0.013% and copper 0.010%, practically the same as the average of the entire list.[4] It would seem that this figure of 0.01% for the average copper content of the Keweenawan traps of the Michigan copper district is a far better one to use than the previous figures, two and three times as large, based upon less complete data. This does not mean, however, that the copper solutions traveled through rock having 0.01% copper. There is reason to believe that some of the chief channels were in felsite conglomerate with a primary copper content of 0.003%.

Studies of polished sections of the traps from this district show the presence of minute quantities of chalcopyrite, bornite, chalcocite, and native copper, in amounts consistent with the range of

[4] Other corrections might be applied. Allowing for the differences in thickness and density of the different flows, the average copper content becomes 0.011%. On the other hand, the inclusion of a felsite flow in the list would make the average lower; so it seems that 0.01 is a fair figure.

figures given above for copper and sulphur. Of these analyses, two thirds have enough sulphur to make chalcopyrite out of all the copper present, and the remainder have enough to make chalcopyrite plus bornite. Thus analyses and polished section examinations show that these lavas are like those from all over the world; they contain a minute amount of copper, largely in the form of sulphide.

GENERAL DISTRIBUTION OF COPPER.

If the copper in the traps had been dissolved in whole or in part by circulating waters, according to the "lateral secretion" hypothesis, then at any one place the remaining copper should represent the original amount minus what had been removed. Thus the remaining copper might be expected to vary with depth from surface, or with proximity to places of copper concentration, or with position with respect to such concentrations. To investigate properly the possibility of such variations would be in itself a study of some magnitude. So far as indicated by present information, there are no known bodies of trap that are leached of their primary copper content. The traps sampled for analysis in the present studies were widely scattered as to areal distribution, place in the geologic sequence, depth from surface, and proximity to ore bodies. The first three samples in the above list are all ophites, and for that reason, at least, may be regarded as comparable. Their copper contents agree fairly closely, yet their distribution varies widely. The one with the copper content of 0.009 per cent. is known as the Kearsarge flow. Locally, its amygdaloidal top has copper mineralization and constitutes the largest amygdaloid ore body known. The sample was taken at a vertical depth of about 3,500 feet and south of the ore body proper but still within a marginal belt where there is scattered mineralization in the amygdaloidal top. In the inclined strata vertically above, the ore bodies in the Osceola amygdaloid and the Calumet Conglomerate are found. Here, if anywhere, the effects of lateral secretion should be evident. The sample was taken in the very heart of that part of the district where the three

lodes credited with 75 per cent. of the copper production of Michigan occur. Yet the copper content is close to the average for all the traps.

The other two ophites, assaying 0.008 and 0.012 per cent. copper, were sampled from much nearer the present surface and from well outside the parts of the district from which important production has come. One of them has slightly less and the other slightly more copper than the Kearsarge-flow sample, which was taken where conditions with respect to lateral secretion possibilities are so entirely different. Thus, the present information regarding the general distribution of primary copper in the traps, so far as it goes, does not indicate any widespread leaching of copper in the zone of observation.

DISTRIBUTION OF COPPER IN INDIVIDUAL FLOWS.

Two of the ophites, the Kearsarge and the Greenstone, were sampled at intervals from top to bottom, and the distribution of copper with respect to other constituents and to position in the flow was studied.

The Greenstone is the greatest flow in the district and, where sampled, is 1239 feet thick. In the upper half of the flow are intermittent tabular bodies of high density consisting of coarse-grained aggregates of feldspar, magnetite, pyroxene, ilmenite, and other constituents. They lie parallel to the flow surfaces, are coarser than the adjacent ophite, and grade into it. They are believed to have been formed with the aid of mineralizers liberated from the flow magma itself and are thus regarded as a sort of basalt pegmatite, commonly known as "dolerite."[5] The explanation of their origin by a process of differentiation by volatile transfer seems inescapable.

The entire flow was divided into 12 parts for analyses. The sampling was carried continuously throughout the flow, the entire group of samples being made up of 154 pieces of drill core. The

[5] Lane, A. C.: The Keweenaw Series of Michigan. Mich. Geol. and Biol. Survey, Pub. 6, Geol. Ser. 4, Vol. 1, pp. 134–136, 1909; Butler, B. S. and Burbank, W. S.: *Op. cit.*, p. 24.

doleritic streaks are confined entirely to the upper half of the flow. Two of them, 32 and 4 feet thick, were sampled separately; they are shown in Fig. 1, at depths of 210 and 285 feet respectively.

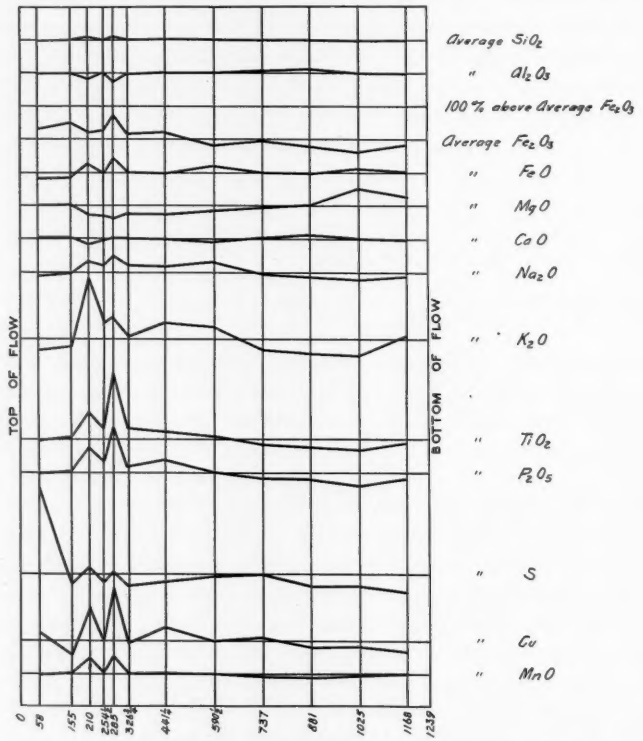

FIG. 1. Variation of oxides with depth, the Greenstone flow.

The copper and sulphur content of the various samples taken in the Greenstone flow is given in the following table (page 307).

The calculated weighted average for the entire flow, allowing for thickness and specific gravity of each sample, is sulphur 0.023, and copper 0.012 per cent.

Depth from Top of Flow.	Middle of Sample at	Thickness.	Sulphur per cent.	Copper per cent.
0–116	58	116	0.082	0.015
116–194	155	78	0.015	0.007
194–226	210	32	0.025	0.023
226–283	254½	57	0.016	0.011
283–287	285	4	0.022	0.029
287–366.5	326¾	79.5	0.014	0.011
366.5–516	441¼	149.5	0.018	0.017
516–665	590½	149	0.021	0.012
665–809	737	144	0.022	0.013
809–953	881	144	0.014	0.010
953–1097	1,025	144	0.014	0.010
1097–1239	1,168	142	0.010	0.008

In Fig. 1, each sample is represented by a vertical line whose position is determined by the midpoint of the interval sampled. Thus, the sample representing the interval extending from 809 to 953 feet from the top of the flow is plotted at 881 feet. For each chemical constituent, a horizontal line which represents the average content of that constituent for the entire flow is drawn. The broken lines represent the percentage variation of each constituent in the different samples, above or below the average. Thus the doleritic streak at 285 is seen to have a ferric oxide content of about 75 per cent. above the average for the entire flow. The sample has a magnesia content of about 40 per cent. below the average.

It will be noted that there is a characteristic type of curve which expresses the distribution of most of the constituents. One of its outstanding features indicates the great percentage increase of the various constituents in the doleritic streaks shown at depths of 210 and 285 feet. The constituents that show this characteristic curve are MnO, Cu, S, P_2O_5, TiO_2, K_2O, Na_2O, FeO, Fe_2O_3, and SiO_2.

Thus the copper has a purely magmatic distribution throughout the flow, conforming in detail with the other constituents of both rock-forming and accessory minerals as listed above. Polished sections of the doleritic streaks, which are highest in copper, show the presence of chalcopyrite and bornite. Certainly there is no essential modification of the primary copper here by later solu-

tions. However, this flow where sampled is in a part of the district where the ore bodies are small and unimportant, and perhaps the advocates of lateral secretion would not expect to find its effects outside the immediate vicinity of the ore bodies.

The Kearsarge flow, however, as already stated, was sampled at a vertical depth of 3,500 feet, directly below the Osceola-amygdaloid and the Calumet-conglomerate ore bodies and within the marginal zone of mineralization surrounding an important ore body in its own amygdaloidal top. Here lateral secretion effects, if they exist at all, might more reasonably be expected to be found.

The copper and sulphur content of the various samples taken in the Kearsarge flow is as follows:

Depth from Top of Flow.	Middle of Sample at.	Thickness (feet).	Sulphur per cent.	Copper per cent.
0–12	6	12	0.012	0.006
12–23	17½	11	0.014	0.016
23–37½	30¼	14½	0.004	0.005
37½–69½	53½	32	0.006	0.004
69½–101½	85½	32	0.003	0.006
101½–133½	117½	32	0.010	0.011
133½–164½	149	31	0.012	0.014

The calculated weighted average for the entire flow, allowing for thickness and specific gravity of each sample, is sulphur 0.008, and copper 0.009 per cent.

Figure 2 shows the variations of the constituents throughout the Kearsarge flow. Where sampled, the flow is only 164½ feet in thickness and therefore cannot be expected to show the marked differentiation effects shown by the much thicker Greenstone flow. However, there is even here a decidedly characteristic curve shown by MnO, Cu, S, P_2O_5, TiO_2, K_2O, and Na_2O. Although there are no doleritic layers in this flow as there are in the Greenstone, nevertheless the sample shown at 17½ feet, immediately below the amygdular top, has a marked concentration of the constituents named.[6] These are practically the same

[6] Unfortunately the top sample, shown at 6 feet, is the highly fragmental amygdular top and is here full of later minerals such as epidote, calcite, chlorite, and others, making it unsafe to use that particular sample as depicting primary distribution.

constituents as were concentrated in the doleritic layers in the Greenstone, and it is reasonable to ascribe the concentration here to the same process as in the case of the doleritic streaks, namely, volatile transfer.

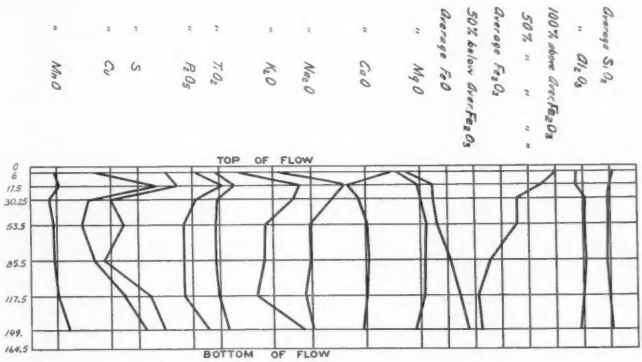

FIG. 2. Variation of oxides with depth, the Kearsarge flow.

Here again, the copper has the same distribution throughout the flow as other constituents, both rock-forming and accessory. No effects of leaching of the primary copper are found, even though the samples came from the heart of the productive part of the district.

VOLATILE TRANSFER AND ORE DEPOSITION.

It is interesting to note how even these lava flows, in spite of the limited time in which differentiation processes acted, show the operation of processes of importance in ore deposition. All of the lava flows gave off gases. The observations of eye witnesses of modern flows, the presence of the vesicular tops, and other well-known evidence make this an undisputed fact. Just what these escaping gases did to the flow itself, especially to the parts already wholly or partly solidified, is not so well known. They oxidized the iron in the flow tops and in places introduced iron to the tops from the main body of the flow. The doleritic layers in the Greenstone are obviously the effects of volatiles which ascended

at intervals through the liquid portion of the cooling flow and, on becoming trapped below the solidified portion, altered and replaced it and introduced the constituents carried upward as or by the volatiles. They offer somewhat the same type of evidence of transportation in the gaseous state as do fumaroles. With the lava flows, however, the fact that the source of the volatiles is known and is right at hand available for analysis and examination makes possible a quantitative study not possible with fumaroles.

Thus it is apparent from a study of the Greenstone that there is a concentration of quartz in the doleritic phases. It may be seen in thin sections, and the calculated norm shows quantities up to nearly 3½ per cent. In appraising the significance of this occurrence it must be borne in mind that the Greenstone as a whole is deficient in silica. It averages 4½ per cent. normative olivine. Both K_2O and Na_2O show high concentration in the doleritic phases, the former more so than the latter. Both ferrous and ferric iron were transported, as was TiO_2 also. The hand specimens show a high concentration of magnetite and ilmenite, and magnetic observations across the outcrop of the flow show strong attraction to exist in the upper portion where the doleritic layers occur. The prevailing notion that magnetite is concentrated near the base of lava flows by crystal sinking or any other process needs checking. In both of the flows studied, the magnetite content of the lower portion of the flow is below average, and there are marked concentrations of both magnetite and ilmenite in the upper portions.

In addition to normative quartz, K_2O, Na_2O, Fe_2O_3, FeO, and TiO_2, there are the concentrations of P_2O_5, S, Cu, and MnO in the upper portions of the Greenstone, especially in the doleritic layers shown at depths of 210 and 285 feet. The constituents that are less in the doleritic layers are Al_2O_3, MgO, and CaO. It is interesting to compare these two lists with similar ones drawn up from observations of volcanic fumaroles and from theoretical considerations. Fenner [7] has developed an impressive argument

[7] Fenner, C. N.: Pneumatolytic Processes in the Formation of Minerals and Ores. Ore Deposits of the Western States, pp. 58 to 106. Amer. Inst. Min. and Met. Eng., New York, 1933.

to prove that the evolution of many of the constituents of ore deposits from the parent magmatic source takes place in the gaseous phase. Bowen [8] lists the following elements which from general considerations would be expected in the gaseous phase: "H, O, Cl, Si, F, S, B, K, Na, Fe, Ti, Al, together with Sn, Pb, Cu, Zn, Ag, and a number of others. The prominent rock-forming elements Ca and Mg we should expect to be hardly represented at all." This corresponds closely to the lists showing the constituents concentrated in the doleritic zones of the flows and those not concentrated in these zones. The one exception is Al, which Bowen lists with those to be expected in the gaseous phase, but which does not occur concentrated in the doleritic layers. Fenner,[9] in discussing Al, states that while its chloride is among the most volatile, its tendency to react with H_2O to form oxide may prevent Al from being carried far or may diminish to a great degree its escape from the magma. This would explain its failure to be found concentrated in the doleritic zones of the lavas.

That these gaseous transfers of material from the body of the flow magmas to the upper crust are not confined to the later stages of solidification is indicated by their effects upon the fine-grained upper portions of flows like the Kearsarge, only 164½ feet in thickness. The period of crystallization of such a flow would indeed be short compared with that of great intrusive bodies, yet the zone from 12 to 23 feet from the top, which is rather fine-grained, quickly chilled material, apparently formed the roof against and into which the gases came from the still liquid main body of the flow, adding the various constituents already listed.

When differentiation by gaseous transfer in these relatively thin, quickly chilled, surface flows can increase the concentration of certain elements, like copper, one hundred per cent. and more in certain horizons, it is not difficult to picture the possibilities in the great magma chambers of large intrusives.

[8] Bowen, N. L.: The Broader Story of Magmatic Differentiation Briefly Told. Ore Deposits of the Western States, p. 120. Amer. Inst. Min. and Met. Eng., New York, 1933.

[9] Fenner, C. N.: *Op. cit.*, p. 84.

SUGGESTIONS FOR FURTHER WORK.

These doleritic or pegmatitic layers are worthy of further study. The doleritic layers of a thick flow, like the Greenstone, should all be studied to see what differences the successively deeper ones would show. The distribution of some of the rarer elements might be included in the study.

Grout [10] cites an interesting test made on a Keweenawan trap sample from Crooked Creek, Minnesota. The sample ran 0.020% total copper, but only 0.002% to digestion in nitric acid. From this the conclusion is drawn that "the copper is in the form of an insoluble silicate, rather than a sulphide or native copper." This conclusion as it stands cannot be accepted for the Keweenawan of the Michigan copper district, inasmuch as the sulphides can be seen in polished sections of the traps, and there is enough sulphur in all the samples to make chalcopyrite or bornite out of all the copper. However, this does not mean that it has been proved that *all* of the primary copper of the Michigan traps is present as sulphide (or native copper). Grout's method of analysis might well be tried to see whether any of it is in minerals that do not yield to digestion in nitric acid.

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[10] Grout, Frank F.: Keweenawan Copper Deposits. ECON. GEOL., vol. 5, p. 475, 1910.

"LIMONITE" OF MOLYBDENITE DERIVATION.

ROLAND BLANCHARD AND P. F. BOSWELL.

MOLYBDENITE is the one sulphide, other than covellite, whose oxidation products may be readily confused with those of chalcocite.

When massive, molybdenite oxidizes normally to molybdic ocher, a yellow-buff to slightly greenish buff product, earthy to finely granular, so individual in color and appearance as not to be easily confused with beaverite, carnotite, or other secondary products of somewhat similar color and texture which it superficially resembles.[1]

Where disseminated, especially in the presence of pyrite, chalcopyrite, or other acid-yielding sulphide, molybdenite commonly leaves behind as the final oxidation residual a product wholly free from the yellowish to greenish buff molybdic ocher. The product is a typical limonite,[1] in some instances so similar in appearance to that yielded by disseminated chalcocite that, upon superficial examination, it may be readily mistaken for the latter.

Our first experience with this product occurred near Chloride, Arizona, where a maroon-colored indigenous limonite, filling the cavities left by disseminated molybdenite, was especially misleading because it occurred in a disseminated copper area whose chalcocite likewise yielded an indigenous limonite of that color. At first glance an extensive acreage of good grade disseminated chalcocite ore was indicated. Careful inspection showed, however, that an important percentage of the limonite in question was of molybdenite origin.

[1] Although the chemical composition of molybdic ocher as given by Schaller ($Fe_2O_3.3MoO_3.7\frac{1}{2}H_2O$) shows Fe_2O_3 and H_2O, molybdic ocher as observed by us in the field in its purer state carries no visible "limonite." Where "limonite" is present, it has been observed to occur as a separate mineral. The term "limonite" is here used in the same sense as in previously published papers on Leached Outcrops.

Since then this type of limonite has been observed at numerous places in the Southwestern States and Mexico, and at several places in Australia.

No difficulty should be experienced in differentiating the molybdenite from the chalcocite product, if the limonite within the cavities is examined with the hand lens; for the two limonite types of molybdenite derivation that have been differentiated to date—foliated boxwork and granular structure—possess clearly distinguishing characteristics.

FOLIATED BOXWORK.

Of the two types named, foliated boxwork is the more abundant and the more characteristic. In a feldspar gangue it generally occurs as an extremely thin-walled limonite product with well defined foliated pattern. The structure is too small to be successfully photographed, but typical examples have been sketched. They are shown in Fig. 1.

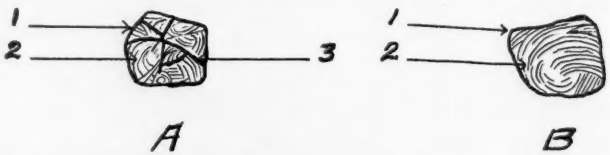

FIG. 1. Foliated boxwork of molybdenite derivation. *A*. Santo Niño deposit, near Nogales, Arizona. *B*. Hodgkinson district, Queensland. (1) Outline of cavity. (2) Foliated limonite flakes. (3) Hypogene quartz veinlets. × 20.

Cell flakes are extremely thin, being in that respect similar to "cleavage" boxwork of galena derivation; they range in thickness from 0.005 to 0.03 mm. They are comparatively smooth and rounded, not crinkly like those of sphalerite derivation. Neither do their surfaces ordinarily carry the coatings of limonite grains, characteristic of sphalerite-derived limonite, nor the finely nodular films from oxidizing pyrite that so frequently encrust cell walls of the limonite derived from disseminated chalcocite.

These characteristics, together with the foliation, serve to differentiate the molybdenite product from the chalcocite derivative.

The color of foliated limonite is not constant. It ranges from tan, through orange, to maroon. Owing to absence of the finely nodular crusts of pyrite derivation, the color never becomes the seal brown to nearly black shade so common to limonite of disseminated chalcocite origin. Ordinarily a single color, such as tan or maroon, characterizes the limonite that fills an individual cavity, but in some instances several colors are present. Where this occurs, the colors have been observed to be mutually exclusive, one portion being tan, the other maroon, with no intermixture. The presence of different colors of limonite has not been observed to coincide with the presence of a specific foreign sulphide, such as pyrite or chalcocite, nor necessarily to denote the presence of any other sulphide whatever; both the tan and the maroon limonites develop side by side where molybdenite constitutes the sole sulphide, and both have been found side by side in the same gangue, such as monzonite or granite. Among igneous gangues, however, the maroon color has been noted as most abundant in those of moderately strong neutralizer.

Because of its thin cell flakes, and the resulting fragile structure, foliated boxwork is readily whipped out by weathering. Consequently, it is not found well developed directly at the surface except in sheltered positions. This adds to the confusion in differentiating it from the chalcocite product, because an indefinite maroon limonite aggregate often remains within the cavity as indigenous limonite with no visible foliated structure to designate its parentage. In such cases it is necessary only to break the rock so as to expose a fresh surface an inch or two beneath the outer surface in order to reproduce the foliated structure of molybdenite, or the characteristic one of chalcocite, derivation.

GRANULAR TYPE.

In certain districts limonite of molybdenite derivation is granular, with foliated boxwork largely or wholly extinguished. Granularity seems to coincide with existence of intergrown molybdic

ocher, little or no molybdic ocher usually being visible where clean-cut foliated boxwork is present. Where the granular product is maroon in color, it is especially likely to become confused with the customary maroon-colored chalcocite derivative.

In case of the molybdenite product, distinguishing features are that the limonite is both granular and slightly greasy in luster, somewhat resembling granular apatite or garnet; and that it is totally devoid of the pyrite-derived finely nodular films or crusts, already referred to in limonite of disseminated chalcocite derivation. Commonly the granular mass, if closely inspected with a 16 × or 20 × hand lens, reveals faint, if nearly obliterated, remnants of either the foliated or a platy, micaceous structure,—often as semi-clayey, semi-greasy petals embedded in the more granular product; but these are not always present.

Excellent examples of the granular type occur at the Santo Niño deposit near Nogales (Arizona). Here little chalcocite exists, the copper sulphide being mainly chalcopyrite. The primary ore is intricately inter-disseminated chalcopyrite and molybdenite in a feldspar gangue. Only minor molybdic ocher is visible in the leached outcrops; but small amounts of it are detectable in the greasy, granular limonite specks, and faint remnants of either the foliated or platy micaceous structure in nearly all cases are distinguishable. They impart to the leached molybdenite product a tan to buff color, whereas the chalcopyrite and chalcocite (rare) products in this deposit leach mostly to a maroon or Indian red limonite, which contains the characteristic boxwork patterns for their respective copper sulphides.

Similar greasy, granular limonite, intermixed with small grains of molybdic ocher, is present in the Hodgkinson District, Queensland, as the oxidized derivative of molybdenite nodules up to one-half inch diameter. At that place the larger, more massive nodules, however, oxidize to pure molybdic ocher.

It is not clear why in some cases molybdenite oxidizes with the production of molybdic ocher, whereas in other cases little or no such ocher is formed, the oxidized product consisting almost wholly of the distinctive foliated or granular limonite derivative.

No convincing field evidence has been found that the limonite product results from long exposure to weathering of molybdic ocher; for the product occurs well developed in districts where erosion keeps nearly abreast of oxidation. The fact that molybdenite-derived limonite mostly coincides with small nodules and disseminated specks of molybdenite suggests that gangue neutralizer may play an important part in determining whether molybdic ocher or limonite is formed. More investigation is needed before a final opinion on this point can be offered.

Since the distinctive foliated pattern for limonite of molybdenite derivation results from pseudomorphic replacement by limonite of a portion of the sulphide structure, no reason is apparent why other sulphides or associated minerals with foliated structure may not yield limonite of a similar pattern.

Possibly some of them do. But not many such minerals are common associates of copper, zinc, or lead sulphides. Of those that are, specularite is probably the most common, especially as regards copper.

Foliated structure might be expected to persevere frequently in the case of specularite, but the result of much field observation is that even where the unoxidized specularite is distinctly foliated or platy, foliated limonite boxwork does not develop importantly from it; cellular limonite that remains as the leached product is either rudely quadrangular in pattern, or assumes an indefinite cellular pattern that may occur in rudely parallel layers but generally becomes largely submerged in an earthy or smeary groundmass.

In any event, such foliated structure, if present, would signify that it was derived from a mineral other than the copper, lead and zinc sulphides, and probably from a useless one where the mining of ores of those metals is concerned. Consequently, it would not be likely to cause confusion unless the ore mineral sought were molybdenite.[2]

[2] We have had no opportunity to extend this investigation to outcrops over the molybdenite deposit at Climax, Colorado. It would be of interest to know how closely oxidation products of molybdenite at that place coincide with the ones herein described.

FIG. 2. Limonite derived from foliated specularite. Marimo, Cloncurry district, Queensland. Note absence of foliated boxwork, and almost complete submergence of an indefinite cell structure in the earthy limonite groundmass. A rude parallelism of the platy structure is preserved. Natural size.

SUMMARY.

1. When massive, molybdenite normally oxidizes to molybdic ocher; when disseminated, or occurring as small seams or nodules, molybdic compounds frequently undergo complete leaching from the cavity or seam, leaving indigenous limonite.

2. Such limonite, because of its not uncommon occurrence in disseminated copper areas, and its common maroon color, may be readily confused with that of chalcocite derivation.

3. Two limonite products of molybdenite derivation—foliated boxwork and granular structure—have been identified. Distinguishing characteristics are listed, which serve to differentiate these products from limonite of related, disseminated copper derivation.

4. Frequent development of indigenous limonite after molybdenite where the molybdenite occurs in small specks, nodules, or seams in contact with moderate or rapid neutralizer, and the more common development of molybdic ocher where the molyb-

denite occurs massive, suggests that gangue neutralizer or infiltrating neutralizer is vital to formation of limonite after molybdenite. This opinion requires further evidence to substantiate it.

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DISCUSSION AND COMMUNICATIONS

THE PROBLEM OF SERPENTINIZATION.

Sir: I wish to comment on discussions of my article on serpentinization,[1] by Mr. Dresser and Mr. Bain, which have appeared in recent issues of this Journal.[2]

Concerning Dresser's Communication: Mr. Dresser criticizes my statement, "The recent work of Keith and Bain shows conclusively that the asbestos veins are fissure fillings, and replacement and recrystallization played very minor rôles in the vein formation," because he believes the evidence I have cited from Keith and Bain's paper was concerned with a slip fiber deposit. Though it is true that the deposit at present being worked on Belvidere Mountain by the Vermont Asbestos Corporation is a slip fiber deposit, the evidence for which I quoted Keith and Bain was taken by them from the Gallagher mine, a cross fiber deposit of the Thetford type.

The other point of Mr. Dresser's criticism concerns my omission of any discussion of the bands of intense serpentinization bordering cross fiber veins. I might well have discussed this point, but did not because the broad field which I wished to cover in my article necessitated omitting discussion of many important details. These bands of intense serpentinization are well described in Mr. Dresser's classic memoir on the Thetford District. I consider them to be wall-rock alterations produced by the solutions which deposited the chrysotile in the veins.

Concerning Bain's Communication: The main point of disagreement between Bain and myself seems to be that Bain contends that serpentinization and the amphibole, chlorite, talc and

[1] Hess, H. H., ECON. GEOL., vol. 28, pp. 634–657, 1933.

[2] Dresser, J. A., ECON. GEOL., vol. 29, pp. 306–307, 1934.
Bain, George W., *Idem*, pp. 397–400.

carbonate minerals of steatitization were all produced by hydrothermal solutions, the source of which was outside of the ultrabasic; whereas I believe that serpentinization was produced by the "stewing of the ultrabasic in its own juice," and that only steatitization was produced by hydrothermal solutions from without. In maintaining this stand, it seems to me that Bain has placed insufficient weight upon a most important fact of the problem—that of the spatial distribution of the alterations. Serpentinization, as I have pointed out, is commonly irregularly distributed throughout the ultrabasic and generally bears no definite relation to the footwall or keel of the ultrabasic; whereas the amphibole, chlorite, talc and carbonate minerals of steatitization are nearly always related to the footwall or borders of the ultrabasic. Because of this relationship I have concluded that the serpentinizing solutions came from within (auto-metamorphic), and that the steatitizing solutions came from without. This conclusion was further strengthened by a number of other points, one in particular being very significant—that serpentinization was always found to be older than steatitization.

I have recently returned to Vermont to go over some of the disputed points with Bain in the field. I do not find it necessary to change any of my conclusions as suggested by Bain. On some of the disputed points I believe Bain has presented possible but less likely interpretations, and on others I frankly disagree as to the meaning of the field evidence. Inasmuch as he infers that my observations were inaccurate, I find it necessary to consider his points one by one.

I do not disagree with Bain as to the size of the ultrabasic bodies, and had no intention of inferring that they were all small. Some of the pinching and swelling sheets which I referred to are miles in length, and other stock-like bodies which I have since examined also have dimensions measurable in miles.

Position of Amphibole in the Mineral Sequence.—Bain's contention is that the actinolite associated with talc in the altered ultrabasics is younger than the talc. His reasons for this contention are as follows:

(1) "Distribution of radiating actinolite in greater abundance along the walls than through the ultrabasics in Vermont, argues strongly against its early development."

(2) The occurrence of actinolite only in those masses which have been moderately to completely steatitized.

(3) The occurrence of extremely delicate sprays of actinolite crystals growing outward from chlorite or biotite walls into crumpled foliated talc. "The delicate actinolite would have been broken had it antedated the crumpling."

Points (1) and (2) seem to me to be indirect, and not compelling, evidence of the relative ages of actinolite and talc; (3), however, is most significant, and I will discuss it first. When I saw with Bain the sprays of actinolite needles radiating into the crumpled foliated talc from the biotite or chlorite walls at the Vermont Mineral Products quarry, I was ready to admit that the actinolite was younger than the talc. I returned, however, and examined the actinolites in more detail, and found that as these actinolites penetrated into the talc (in the direction away from the biotite or chlorite walls) in many cases they became perfect talc pseudomorphs after actinolite (Fig. 1). About these pseudomorphs there can be no doubt, and thus no doubt that the talc is younger than the actinolite. Close examination shows that many of the actinolites are bent or broken, but nevertheless it is remarkable that any needles should remain intact. Perhaps the explanation lies in the extreme softness and plasticity of the talc in which the rigid actinolites are embedded. Where talc has replaced radiating clusters of actinolite in serpentine, a very perfect selective replacement of the serpentine occurs at first, so that it is often possible to find sharply defined clusters of actinolite in a talc matrix. Perhaps these led Bain to conclude that the actinolite replaced talc. With further replacement, however, the actinolite clusters may also be replaced by talc, as shown in Fig. 1.

Concerning the talc pseudomorphs which I mentioned as occurring at the Holden quarry, I wish to make a correction. Bain is partly correct. They are not after actinolite in this particular instance (nor are they acicular talc crystals, as he suggests). Actinolite occurs along the walls, and similar-looking radiating

clumps within the soapstone I took to be talc pseudomorphs after actinolite, though I was not able to find any relics in them at the time. I have since found relics of enstatite which prove that to be the original mineral. In this respect Fig. 6 of my article and my statements on page 644 should be changed.

Concerning Bain's contention (1) listed above, I believe the occurrence of actinolite along the margins of the ultrabasic is due

FIG. 1. Upper half, talc pseudomorphic after actinolite. Lower half, unreplaced original actinolite. Natural size.

partly to the fact that the CaO necessary to form actinolite is available there either from the wall rock or incoming solutions. It is not available within the ultrabasic because the ultrabasic contains practically none. The high-temperature minerals which will crystallize in this CaO-poor environment contemporaneously with actinolite at the border are anthophyllite (such as in the anthophyllite deposits of Georgia or Idaho) or enstatite (such as at the Holden quarry mentioned above, and perhaps also as in the North

Carolina corundum deposits). A second reason for the occurrence of actinolite only at the borders is that the high-temperature stage of steatitization in Vermont has only a very slight development; in most cases it seems that the temperature was barely high enough to form actinolite, and soon fell below that level. Thus the development of high-temperature minerals was largely limited to the border zones.

The explanation of Bain's contention (2) lies in the fact that those ultrabasics nearest the large granite intrusions or source of solutions are most completely steatitized and, being nearest, they also show the best development of the high-temperature stage and thus the best development of actinolite.

Chrysotile Asbestos Veins Remain Within the Ultrabasic.—Although Bain objects to my statement that chrysotile asbestos and ordinary serpentine veins remain within the ultrabasic, he has not found any case where they occur in the country rock away from the ultrabasic. He mentions chlorite veins, but I consider that these are of quite different origin and are related to the younger steatitization.

Distribution of Serpentinization.—I cannot agree with Bain's idea that serpentinization is largely controlled by fractures, and areas of intense serpentinization limited to fracture zones. I have seen many areas only slightly fractured that are over 90 per cent. serpentinized. Some fractures developed in serpentinized areas I would attribute to slight volume changes during serpentinization.

The above refers to the general serpentinization of the ultrabasic; the location and formation of pure serpentine or chrysotile veins is naturally related to and controlled by fracturing. The lenticular, or pinching and swelling form of many of the Vermont and Quebec ultrabasics indicates, I believe, intrusion during deformation. In those cases where deformation continues or recurs during the closing stages of crystallization, fractures formed in the already solidified portions may be filled by the "hypohydrous" solutions which deposit pure serpentine or chrysotile, dependent on some physical condition as yet undetermined.

Serpentine-Talc Relations.—My statement—"Perhaps fifty hydrothermally altered (steatitized) ultrabasics were examined, and in every case chlorite, not serpentine, was developed"—would have been clearer had I added "during steatitization," since the ultrabasics referred to above had been previously serpentinized. Bain's discussion of this point is due to a misunderstanding of my meaning.

Concerning Magnetite.—Bain states that,

> Although every slab of verd antique produced has not come to my attention, those I have studied have a rim of chlorite around all magnetite grains. The magnetite and chlorite seem to have the same origin, whatever that may be; generally it seems to be a change which accompanies serpentinization and is related to the alteration of serpentine to talc.

It is well known that magnetite, as small crystals or a fine dust, is commonly developed along with serpentine and is included in it. Chlorite is not associated with this development of serpentine and magnetite. I have noted that magnetite in many cases accompanies the formation of chlorite in steatitization. Magnetite is not diagnostic of either type of alteration, but is associated with both. Bain's contention, that serpentinization and steatitization are parts of one and the same process because magnetite is associated with both, carries little weight.

H. H. Hess.

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REVIEWS

The Geology and Ore Deposits of the Horne Mine, Noranda, Quebec. By PETER PRICE. Canadian Min. & Met. Bull. 263, pp. 108–140. 1934.

A well balanced description of the geology and ore deposits of this important mine. Twenty-five ore bodies are found in the mine, with exceptional values in gold and copper, and containing selenium and silver as by-products. The oldest rocks are, on the basis of Cooke's work, considered of Keewatin age. They consist of extrusives of intermediate but variable composition, termed "andesites," also rhyolites, rhyolite breccia, and banded tuffaceous rhyolites. In this group is included a quartz porphyry which had previously been called a dacite. The stratigraphic relations of these are not definitely known. The oldest intrusives are of three different ages, and range from gabbro to quartz diorite in composition. They are grouped under the term metadiabase. Later syenite porphyry dikes are followed by still younger diabase. This younger diabase shows wide chill margins, as compared with the early intrusives. The major folding and faulting are believed to be pre-metadiabase in age. The structure is complex and the reader will have difficulty in obtaining more than a sketchy idea of the relations and attitudes of the various types of rock. This is doubtless because of space limitations and the complexity of structure, but one or two vertical sections through the area shown on Figures 1 and 2 would have been appreciated by the reviewer.

Rock alteration is of three main types; silicification, sericitization and chloritization. Ore formation was dependent on highly disturbed structure, since abundant evidence exists that replacement took place along sheared and faulted zones. Two different trends are present on the upper levels, one northeast and the other northwest. Apparently this is not so marked on the lower levels, and the spreading of the ore bodies in the upper levels of the mine reminds one strongly of a similar space relation, found by Billingsley and Locke to be common in ore-bearing districts of the western United States. In general rhyolite was replaced, whereas andesite was not. Massive sulphide deposits are the most important. They consist of about 90 per cent. pyrrhotite and pyrite, with less magnetite, and widespread chalcopyrite. The so called flux ores are fractured siliceous rhyolite, containing pyrite or chalcopyrite with gold values. Two high-grade gold ore bodies containing native gold and tellurides are

in intensely chloritized rock. It would be of much interest to know whether this chlorite differs from that associated with massive sulphide ore. The general mineral sequence was first pyrite, then a lull in the mineralization, followed by magnetite, pyrrhotite, and chalcopyrite, in the order named. Native gold, electrum and tellurides are later. The mineral association of selenium is not given. Presumably silver tellurides are more abundant than gold tellurides but this point is not discussed. The writer gives a good brief discussion of the relative ages of the later diabase and ore, and favors the interpretation that the ores are post-later diabase in age. Others have held the opposite view. Although dikes that transect ore bodies are often said to be later than the ore, the reviewer does not know of any detailed description of their metamorphic effect on massive sulphides. Some descriptions of undoubted examples would be a welcome addition to the literature.

Dr. Price has set an example that other mine geologists might well emulate.

W. H. NEWHOUSE.

Slate in Pennsylvania. By C. H. BEHRE, JR. Pp. 400, pls. 70, figs. 89. Penn. Geol. Survey, 4th Ser., Bull. M–16, 1933.

This bulletin is a comprehensive report on slate in Pennsylvania and incorporates the material of a previous bulletin (M–9) on slate in Northampton County by the same author. Two questions are posed by the author at the start as justification for the study: "Are all the slate deposits that may be of commercial value known? Are the known deposits worked to the best advantage?" Sixty-four pages are devoted to a description of the structure, petrography and origin of slate, and constitute a most admirable presentation of the fundamentals of structural geology as related to slate. Numerous references are cited, including recent studies on slate by Sanders and Schmidt. There are 89 line drawings, mostly showing structural details or diagrams to aid in interpretation of the significance of structure. Those interested in structural geology will find much of value here. Fifty-one pages are devoted to an exposition of the technology of slate, and two hundred and seventy-four to the specific descriptions of individual slate workings, which include a wealth of detail on structural relationships. There are seventy plates, largely photographs. Geologic maps of the Lehigh-Northampton belt and the Peach Bottom district are included, together with large-scale geologic maps of the Pen Argyl-Bangor and Slatington regions. Several minute detailed stratigraphic sections are given for the productive parts of the Martinsburg formation. This report is an admirable monographic study of a region which is credited with production of slate to a total value of

about $70,000,000 between the years 1913 and 1929 inclusive, or approximately 47 per cent. of the total value of slate for the country as a whole during the same period; it excellently supplements the general treatise on slate in the United States by T. N. Dale.

A. F. BUDDINGTON.

Handbook of Chemistry and Physics, 19th ed. Ed. by C. D. HODGMAN, with 33 collaborators. Pp. 1933. Chemical Rubber Publishing Co., Cleveland, 1934. Price, $6.00.

The new edition of this valuable book follows in general its predecessors in arrangement but has 95 new pages, 89 revised pages, and new collaborators. As before, it contains mathematical tables (265 pp.); tables of properties and physical constants (486 pp.); general chemical tables (196 pp.); physical tables relating to properties of matter, heat, sound, light, and electricity; quantities and units; and miscellaneous tables. The additions are many, the most important being x-ray crystallographic data (43 pp.).

It is a handy reference for all scientists and invaluable for the general student, the mathematician, the chemist, the physicist, the engineer, and the geologist.

Through Space and Time. By SIR JAMES JEANS. Pp. 224, figs. 106. Macmillan Company, New York, 1934. Price, $3.00.

This book is based upon the Royal Institution Lectures, December, 1933, "adapted to a juvenile auditory." Written in a more popular style than its predecessors, it takes the reader on a journey through space, where he can look upon the earth, air, sky, moon, planets, sun, stars, and nebulæ. The chapter on the earth is a brief treatise on geology. The style is lucid, the pictures are excellent, and it makes entertaining reading for scientist or layman.

The Rôle of the Deserts, by A. J. MCINERNY. Pp. 43. Pocket Series, Channing Press, London, 1934. Price, 4 s. 6 d.

The author's thesis is that deserts are geological features of economic importance; that they are zones of disinfection, vast fields of evolution under whose influence the jungle man develops the highest human types, and on whose northern fringe is the only place in the world where the white man is produced indigenously. The book contains interesting information regarding deserts and on anthropology and ethnology. Even if unconvincing in part, the thesis is stimulating.

BOOKS RECEIVED.

DAVID GALLAGHER.

Before the Dawn of History. C. R. KNIGHT. Pp. 119, pls. 46. Whittlesey House, McGraw-Hill Book Co., New York, 1935. A collection of the author's superb illustrations of ancient animals together with a popular description of the research that lies behind them.

Geologic Structures. B. WILLIS AND R. WILLIS. Pp. 544, figs. 202. 3rd Ed. McGraw-Hill Book Co., 1934. The old book revised, rearranged, and rewritten. (To be reviewed later.)

Microscopic Determination of the Ore Minerals. M. N. SHORT. Pp. 68. U. S. Geol. Surv. Bull. 825. Washington, 1934. A revision of Part 3, Determinative Tables, of this useful treatise.

Studies on the Alkalinity of Some Silicate Minerals. R. E. STEVENS. Pp. 13, figs. 1. U. S. Geol. Surv. Prof. Paper 185–A. Washington, 1934, 5 cts. A pH study giving index of weathering qualities and effect on ground water of different silicate minerals.

Halloysite and Allophane. C. S. ROSS AND P. F. KERR. Pp. 13, pls. 2, figs. 3. U. S. Geol. Surv. Prof. Paper 185–G. Washington, 1934, 5 cts. Continuation of work on the kaolin group.

Somerset—Windber Folio, Penn. G. B. RICHARDSON. U. S. Geol. Surv. Folio 224. Washington, 1934. Particularly interesting feature is consideration of structural geology of coals of southwestern Pennsylvania.

Natural Gas and Petroleum in Ontario in 1933. R. B. HARKNESS. Pp. 66. Ontario Dept. Mines, 43rd Ann. Rept., Vol. XLIII, Pt. V, 1934. Toronto, 1935. Statistical.

Mining Industry, of Idaho, 1934, 36th Ann. Rept. W. H. SIMONS. Pp. 287. Boise, 1935. A complete record of mines and mining in Idaho.

Contributions to the Study of Coal. Pp. 99. Illinois Geol. Surv., Rpt. of Invest. 32. Urbana, 1934. Contains: A Proposed Simplification of the Parr Unit Coal Formula, G. Thiessen; Ash-to-Mineral Matter Correction in Coal Analyses, G. Thiessen; Unit Coal as a Basis of Coal Standardization as Applied to Illinois Coals, G. H. Cady and O. W. Rees; Study of the Graphical Method of Calculating Pure Coal Calorific Value, G. Thiessen and F. H. Reed.

Contributions to the Study of Coal. L. C. MCCABE, D. R. MITCHELL, AND G. H. CADY. Pp. 61, figs. 11. Illinois Geol. Surv., Rpt. of Invest. 34. Urbana, 1934. Banded ingredients of No. 6 coal and their heating values as related to washability characteristics, and preliminary report on unit coal-specific gravity curves of Illinois coals.

Illinois Mineral Industry in 1933. W. H. VOSKUIL AND A. R. SWEENY. Pp. 69, tables 41. Illinois Geol. Surv., Rpt. of Invest. 36. Urbana, 1934. Preliminary statistical summary and economic review.

SCIENTIFIC NOTES AND NEWS

W. A. Waldschmidt and E. S. Hanley have opened an office at 323 Colorado National Bank Building, Denver, for consulting mining and geological work.

Ralph D. Parker has been appointed general superintendent of the mining and smelting division of International Nickel Company.

J. T. Rooney and A. E. Alexander, of Buffalo, New York, have formed a partnership as consulting mineralogists and chemists, but retain their respective connections with the Spencer Lens Company and the Buffalo Museum of Science.

The Kansas Geological Society will hold its Ninth Annual Field Conference August 25 to September 1, with an itinerary extending from Iowa City through Wisconsin and concluding at Minneapolis and Duluth, Minnesota. The object is a study of the geology of the Upper Mississippi valley, with particular attention to oil geology. Anthony Folger, 1107 Union National Bank Building, Wichita, Kansas, is in charge of registration.

The Fifth Annual Field Conference of Pennsylvania Geologists will meet at Philadelphia, May 31–June 2, with headquarters at the Academy of Natural Sciences. The trips planned are:—May 31—Physiography of Piedmont Upland and Coastal Plain around Philadelphia, a mineralogic and petrologic trip; June 1—Crystallines and Intrusives near Philadelphia; June 2—Lower Paleozoic and Martic Overthrust, west of the city; June 3—optional excursion to Coastal Plain of New Jersey. Edward H. Watson, Bryn Mawr College, is chairman of arrangements.

EMMONS MEMORIAL FELLOWSHIP

The Emmons Memorial Fellowship in Economic Geology is available for this year (stipend $1,500). Applicants should be qualified by training and experience to investigate some problem in economic geology and should submit a definite statement of their problem to the Committee, under whose oversight the work will be undertaken at any institution approved by them. The Fellow must give his entire time to the problem, which may be used for a doctorate dissertation. Applications and accompanying testimonials should be submitted not later than May 10. Application blanks and further information may be obtained from Alan M. Bateman, Charles P. Berkey, Waldemar Lindgren, or the Secretary, Columbus University.

Correction. Volume 29, page 783, last paragraph, second line. Name of author should be Laffitte, not Lafille.

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